Intraocular lens characterization using a quadric-wave lateral shearing interferometer wave front sensor

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ABSTRACT

We present the application of Quadri-Wave Lateral Shearing Interferometry (QWLSI), a wave front sensing technique, to characterize synthetic intraocular lens (IOL). Wave front sensing is not only a tool to quantify optical quality, but also to map the local (dust, scratches) or global possible defects. This method offers the crucial advantage that it yields an analyzed wave front without the use of a reference arm and consequent time consuming alignment. Moreover thanks to the acceptance of QWLSI to high numerical aperture beams, no additional optics is required. This makes lens characterization convenient and very fast.

We will first explain the QWLSI design and metrological properties (high resolution and dynamic) and its analysis features (aberration measurement, MTF evaluation). We will present our device KALEO for characterization of IOLs. We will particularly show aberrations and MTF measurements of monofocal spherical IOLs. We will present how the QWLSI can answer to the specific analysis of aspherical IOLs. We will finally show a complete characterization of multifocal IOLs in one measurement helping the propagation theory.

1 INTRODUCTION

Cataract surgery is the most frequently performed surgical procedure for adults. It consists in the replacement of the eye crystalline lens by a synthetic intraocular lens (IOL). Therefore IOL manufacturing is a growing and very dynamic market. A few years ago, only simple monofocal bi-convex lenses were implanted. Novel methods for improvement of IOLs in the field of ophthalmology comprise surface shape modifications that differ from perfect spherical geometries of the optical surfaces. Besides correction of spherical refractive vision errors, these surface modifications allow the restoration of the optical properties of the healthy natural human lens. In order to match the implant with the particular optical properties of the patient's optical system, the IOL is designed to exhibit different but well defined optical properties depending on its surfaces geometry.

For instance, to compensate presbyopia, multi-focal lenses have been proposed. Like multifocal glasses, these IOLs have different foci corresponding to near and distance vision.

A lot of measurement tools are available to characterize monofocal IOLs. They are based on contrast measurement

(Modulation Transfer Function or MTF). However these methods are not relevant enough to investigate the properties of a multifocal IOL. Wave front sensing is a better solution as the transmitted wave front gives not only information on the optical quality but also leads to optical power maps and allows to determine the foci positions.

At PHASICS, we have developed a measurement tool named KALEO, based on our commercial wave front sensor SID4. Thanks to its acceptance of high numerical aperture beams without any additional relay lens, the measurement scheme is very simple.

In this paper, we will first present PHASICS SID4 technology, named Quadri-Wave Lateral Shearing Interferometry (QWLSI) and the principle of the KALEO measurement machine. We will then show examples of IOL measurements.

2 QUADRI-WAVE LATERAL SHEARING INTERFEROMETRY

In the 90s, the concept of lateral shearing interferometry has been extended to more than 2 waves by Primot and coworkers [1]. This has lead to the invention of multiwave lateral shearing interferometry and, in particular, to the compact quadri-wave lateral shearing interferometer (QWLSI). The principle of this technique is very simple : the wave front is divided in replicas by a diffractive optics (see Fig 1). Each replica propagates and therefore separates from the other ones. In the region where they still overlap, the interference pattern gives access to the phase difference between each couple of diffraction orders. Because they have separated and if the propagation is short enough, this phase difference is proportional to the local phase gradient. Consequently each couple of replica gives an information on the gradient along one direction (which is determined by the two replicas k-vector difference). The phase gradients are recovered thanks to Fourier analysis around each carrier-frequency associated to each replica couple.

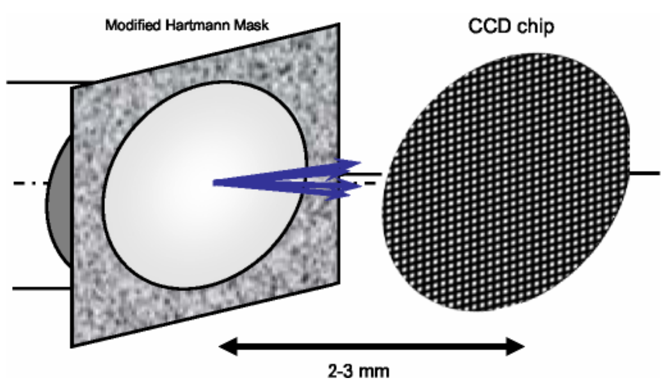


Fig 1 : Principle of the Multi-Wave Lateral Shearing Interferometry, illustrated in the case of four wave interference. The beam is incident from the left. It is first diffracted and the interferences are recorded by the CCD chip.

This principle has been applied in laser metrology to 3-wave interferometers [2], which is its simplest variation. The optimization process led to 4-wave interferometers, thanks to the so-called Modified Hartmann Mask (MHM) [3]. This 2D diffractive optics has been designed to concentrate more than 90% of the power in the 4 first +/-1 diffraction orders only. It is therefore a good candidate to make a Quadri-Wave Lateral Shearing Interferometer (QWLSI).

In the case of QWLSI, the observed interference pattern is a Cartesian grid of sinusoidal fringes. If the wave front is flat, the grid pitch is the same everywhere in the pupil. If the light contains aberrations, the grid is deformed and the deformations are proportional to the local phase gradients.

3 KALEO MEASUREMENT MACHINE PRINCIPLE

To characterize small optics, such as IOLs, we have developed the KALEO measurement machine. Its principle is very simple: a calibrated collimated beam propagates through the lens. The transmitted wave front is analyzed with a SID4 wave front sensor. If the lens is perfect, it is spherical. The distance to a sphere is then the lens aberrations. From the aberration map, we can simulate the Point Spread Function (PSF) and deduce the Modulation Transfer Function (MTF). We can also generate a curvature map and compare it to the IOL design.

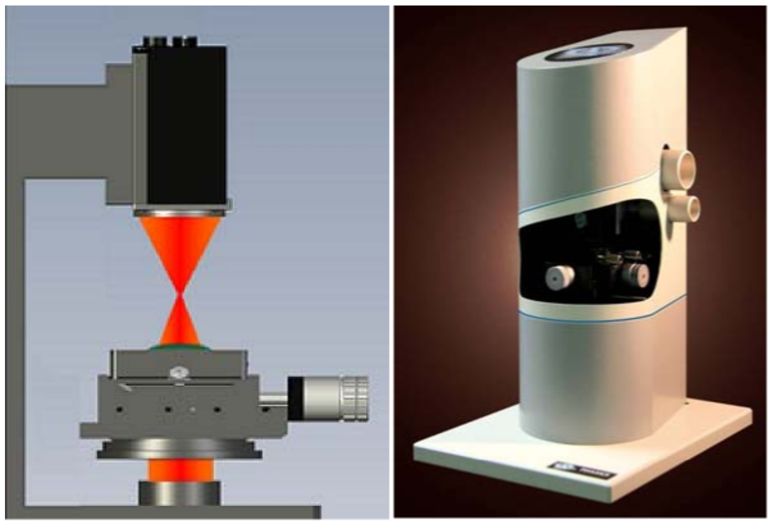


Fig 2 : KALEO measurement machine principle and photograph.

This design permits to measure IOLs in different experimental conditions. We can add a lens to simulate the cornea. In this case we measure aberration of the cornea IOL couple. We can also put IOLs in a saline solution. This technique allows to simulate aberration in vivo condition.

4 INTRAOCULAR LENS CHARACTERIZATIONS

This method can be applied to any kind of refractive IOLs, either spherical, aspherical, monofocal or multifocal. In this paragraph we detail some examples on these optics.

4.1 Monofocal IOL

IOLs currently used in the cataract surgery are monofocal spherical lenses. It is a bi convex lens with two different curvature radii. Intrinsically this optic has spherical aberration. We measure a 22D spherical IOL on 4.8mm diameter. The phase map obtained is shown in Fig 3 (a). We project this map on the Zernike functions to obtain aberration description. The main aberration measured is spherical aberration whose Zernike coefficient is 0.084µm in RMS. Also, from this map we calculate the MTF curve of this lens. Result is shown on the Fig 3 (b). In red we can see MTF curve without aberration; the cut off frequency equals 188 cc/mm (λ=635nm). The black curve is the IOL MTF curve. Its shape is the consequence of spherical aberration.

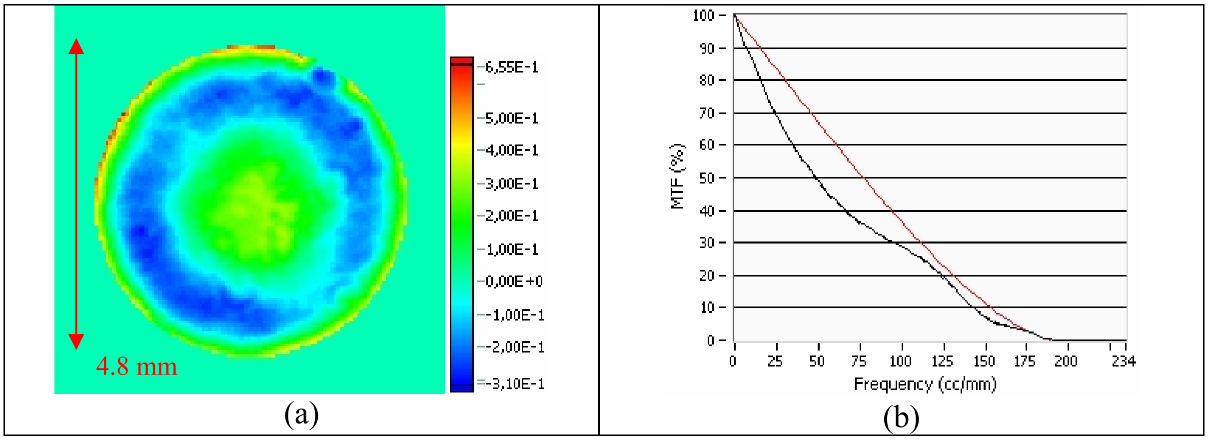


Fig 3 : Measurement of a 22D monofocal spherical IOL with the KALEO machine.
On the left we show the aberration map. On the right we show a MTF curve deduced from the wavefront measurement

Most of aspheric lenses are created with specific functions. Certain have no spherical aberration. Others compensate the spherical aberration of cornea. The spherical aberration of cornea is A COMPLETER AVEC ARTICLE. Therefore, it is just necessary to create a negative spherical aberration. In these two cases, the wavefront analysis permits to measure directly their function. Two examples are showed on the Fig 4. First we measure aberration of IOL without spherical aberration (a). We obtained a spherical aberration Zernike coefficient of 0.002µm RMS on a 4.5mm diameter pupil. This value is very weak and near the SID4 measurement noise (λ/500). The second example is an IOL compensating the cornea spherical aberration. The pupil analysis diameter is 4.8mm. We obtained a Zernike coefficient of -0.260µm RMS. We measure a negative spherical aberration as expected.

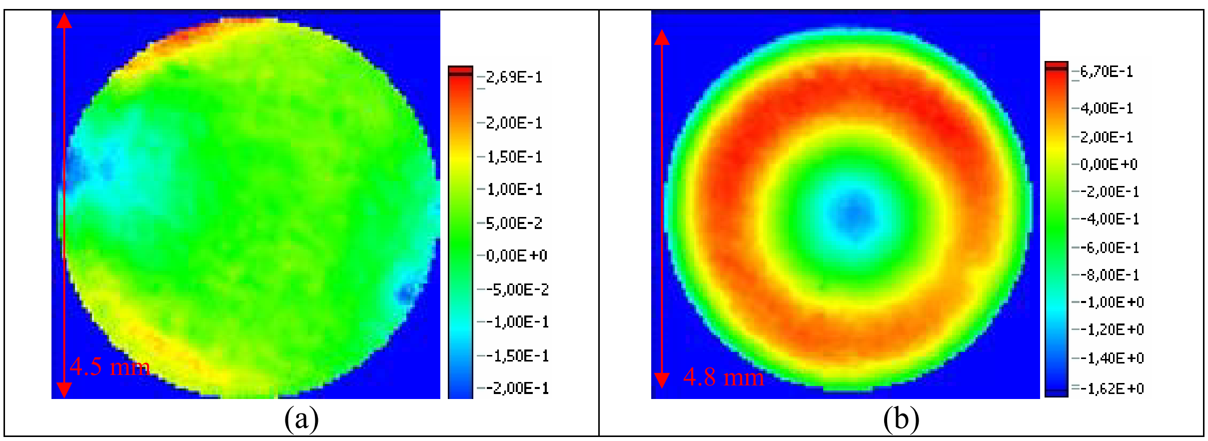


Fig 4 : Measurements of two aspheric lenses with KALEO machine. On the left we show the aberration map of a lens without spherical aberration (21D). On the right we show the aberration map of a lens compensating the cornea aberration (22D).

In these examples, we have shown that wavefront analysis is adapted to characterize IOL. Its interest is even greater for IOLs with specific optical functions.

4.2 Multifocal refractive IOL

Multifocal refractive IOL is a specific optic. Indeed, it permits to focus in near and far vision. That is why it has two different powers. One of the optical designs is to alternate areas corresponding to each vision type (see Fig 5). This is an original optic because one object creates two images. It is the brain that selects the good image. The idea to create this function is based on axis aberrations (see Fig 6). Indeed, spherical aberration has two specific focal planes, marginal and paraxial. The IOL conception consists in calculating axis aberrations coefficients in order to obtain the IOL wanted.

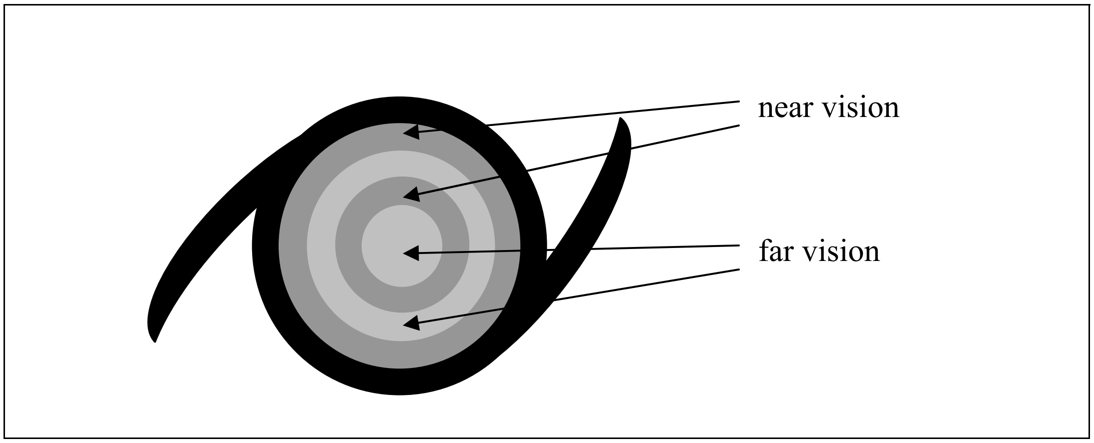


Fig 5 : Example of multifocal refractive IOL design.

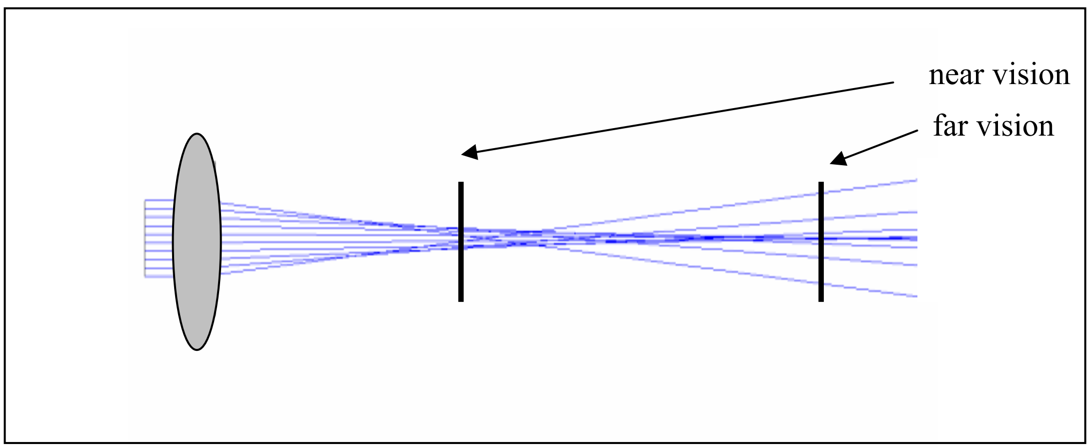


Fig 6 : Example of multifocal refractive IOL optical path.

We have measured this optic and the result is shown on the Fig 7. We observe some centered rings. Thus the phase has a high order of axis aberration. We project this phase map on Zernike functions until 10^{th} polynomial order, thanks to the SID4 which has a high resolution. Results are detailed on the Fig 8.

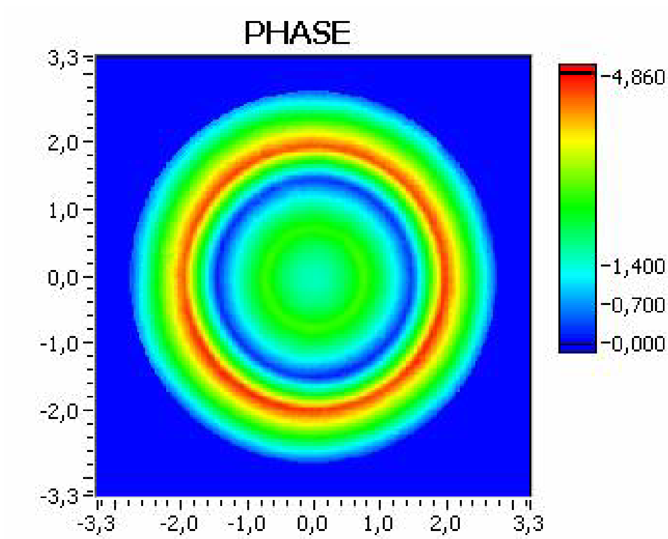


Fig 7 : Phase map of the multifocal refractive IOL (22D 4D).

Number of Zernike polynomial (OSA index)	11 (ρ^4)	22 (ρ^6)	37 (ρ^8)	56 (ρ^{10})
Coefficient value (RMS)	-0.653 λ	-0.615 λ	0.447 λ	0.330 λ

Fig 8 : Zernike coefficient of the multifocal refractive IOL (22D 4D).

We see important contribution of all axis aberrations. This is normal because the lens must generate a large caustic in order to have two focal spots with a difference of 4 dioptries.

With the wave front measurement, we can calculate the IOL power map. We can propagate the wave front in almost any plane. In this case, we can determine the long and short vision focii and deduce their optical transfer functions.

a) Power map

With the phase map it is possible to calculate the local curvature of IOL. After calculation we obtain a cartography of curvatures. This gives which areas correspond to which optical power. We extract a profile of phase map and we draw on the curvature obtained with the power map. The result is shown in the Fig 9. In red we draw the curvature corresponding to the near vision (V+), in green that of far vision (V-). Curvatures are negatives and positives because wavefront is calculated with the reference sphere placed in the caustic waist. We see 4 areas which are alternately far and near vision. The difference of curvatures is 4.0D (±0.5D). There is a good correspondence between the measurement and the IOL specification.

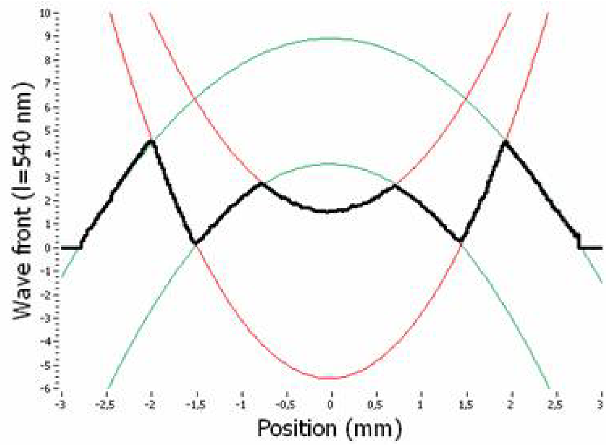


Fig 9 : Phase map profile of multifocal refractive IOL (22D 4D).

b) PSF and MTF

We have seen that we can calculate PSF and MTF with phase and intensity map in one plane. In this case this calculation is going to give the PSF and MTF in caustic waist. This information is not the most pertinent. It would be better to know the PSF and MTF for the far and near vision. For this we calculate the beam propagation in the specific planes.

To validate our propagation algorithm we compare the simulated PSF and a measurement on a CCD camera. We choose three positions, near vision, caustic waist and far vision. Results are showed on the Fig 10. We see the caustic waist PSF is the smallest. In far vision the PSF is large but there is little energy in the rings. So the imaging IOL quality is maximal in far vision. Now, if we compare simulated pictures and measurements, There is a good agreement. So this method is completely adapted to characterize multifocal IOLs in one measurement.

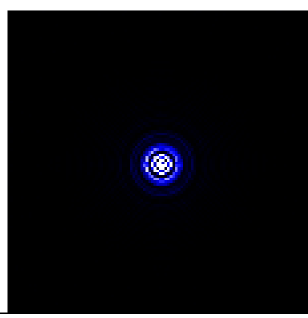
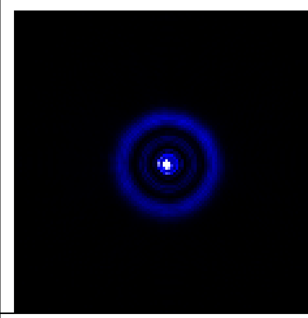
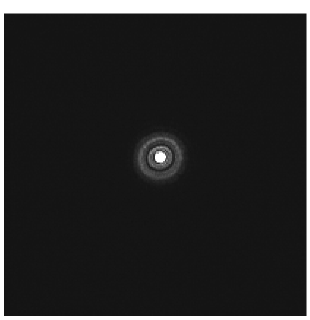
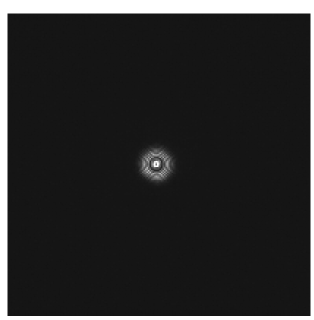
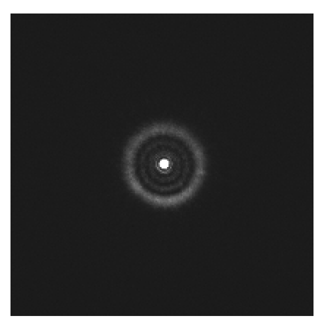
	Near vision	Caustic waist	Far vision
Simulated pictures			
CCD measurements			

Fig 10 : Comparison between PSF calculated and CCD measurements

This method allows to calculate PSF in all the focal planes. So it is possible to calculate MTF in these planes too. We decide to draw some MTF curves in function of the position of the best focus (see Fig 11). We select three frequencies, 10cc/mm, 20cc/mm and 50 cc/mm. For all curve the maximal contrast is obtained for the far vision. We distinguish the near vision but the image quality is not very different from the best focus.

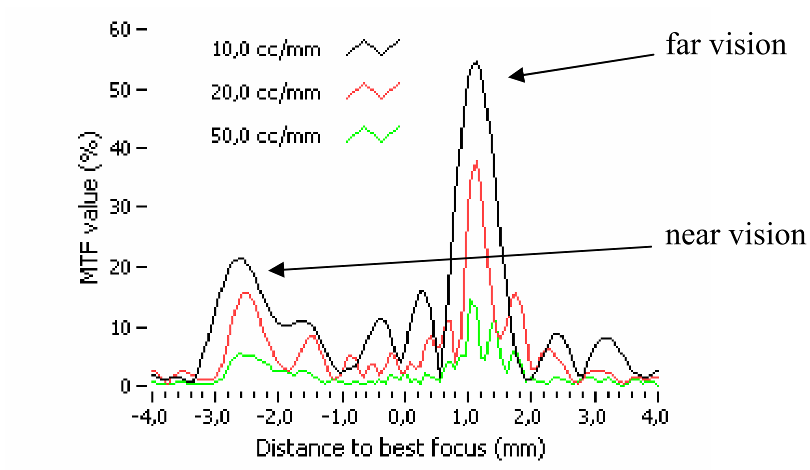


Fig 11 : MTF curves of multifocal refractive IOL (22D 4D).

5. CONCLUSION

We have shown that wave front sensing is a very good solution to intraocular lens characterization, because a wave front transmitted through a lens carries a lot of information about its optical properties in its focal plane(s). It is adapted to characterize spherical, aspheric and multifocal IOLs. In the last case, it is possible to know in one measurement the MTF through frequency curves.

Thanks to its acceptance of high numerical apertures (over 0.3), PHASICS SID4 wave front sensor makes this measurement very fast and simple.

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