Università di Brescia

Dipartimento di Scienze Cliniche e Sperimentali

Dottorato di Ricerca in
«Intelligenza Artificiale in Medicina e Innovazione nella Ricerca clinica e metodologica»

Coordinatore: Prof. Domenico Russo

Design and preclinical validation of a multifocal meta-IOL (Metasurface intraocular lens): an integrated approach between optics, clinical practice and bioengineering

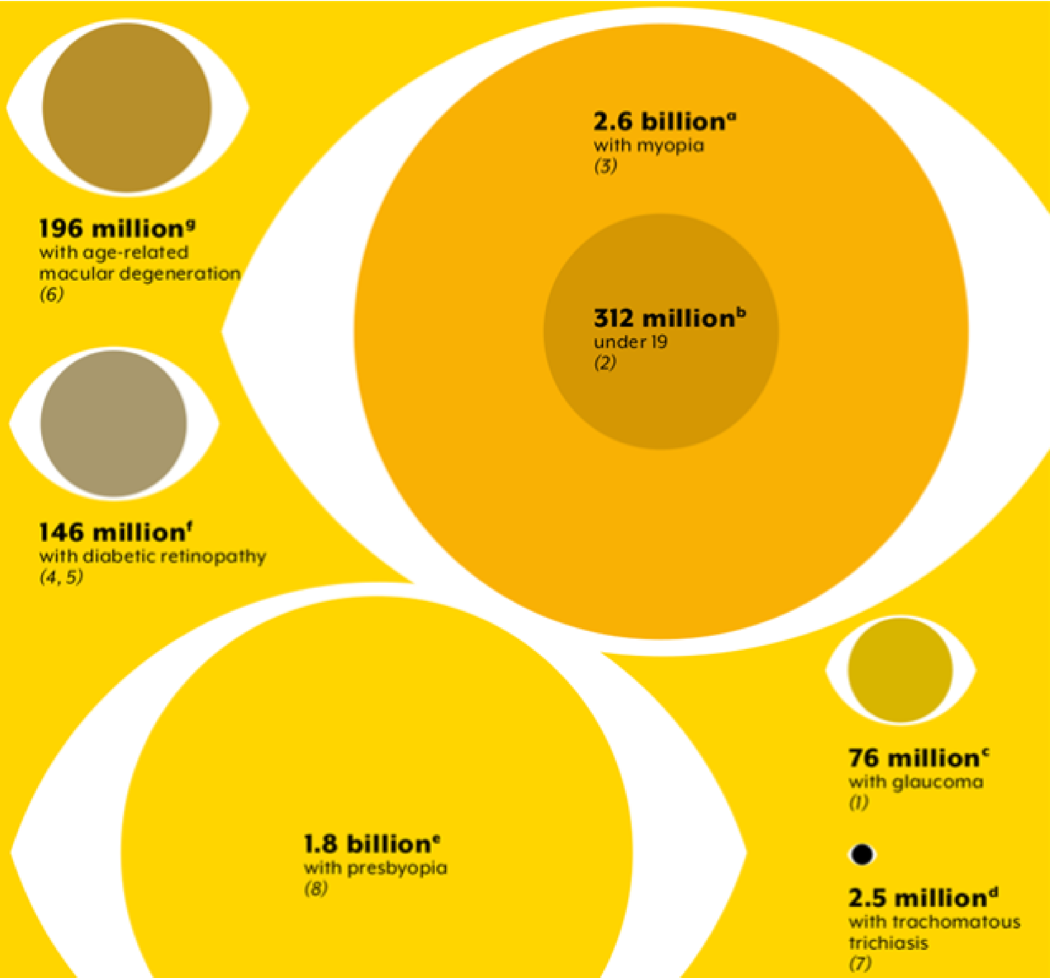
Mekonen Tsedalu Fentaw

CICLO XLI – Curriculum Innovation in Clinical and Methodological Research

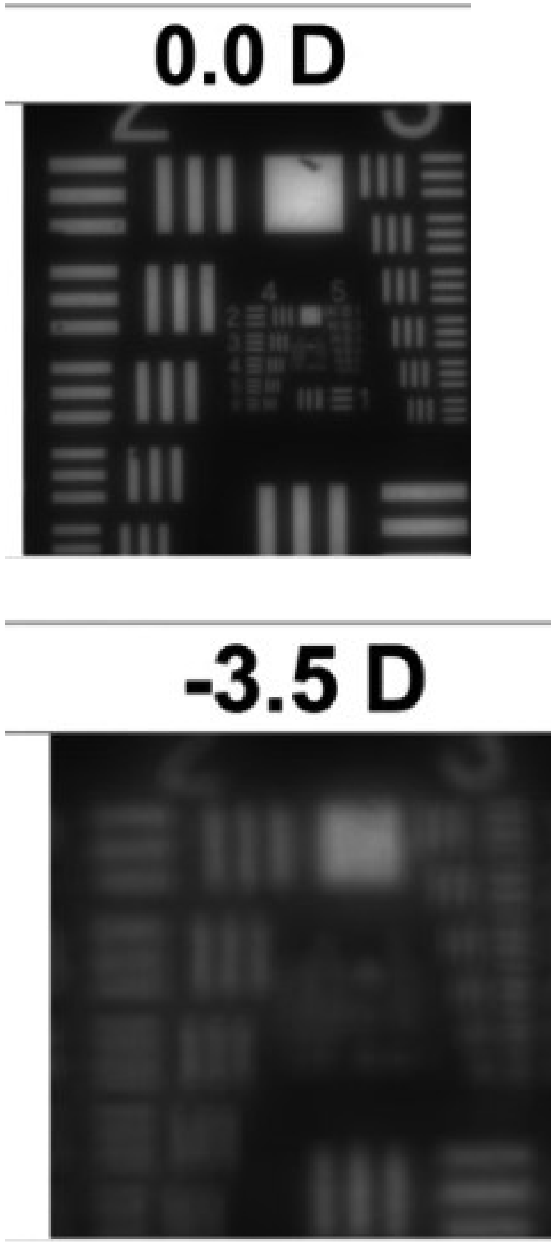
Supervisor: Prof. Costantino De Angelis, and Prof. Vito Romano

Co-Supervisor: Dr. Marco Gandolfi

Motivation



Importance/global need

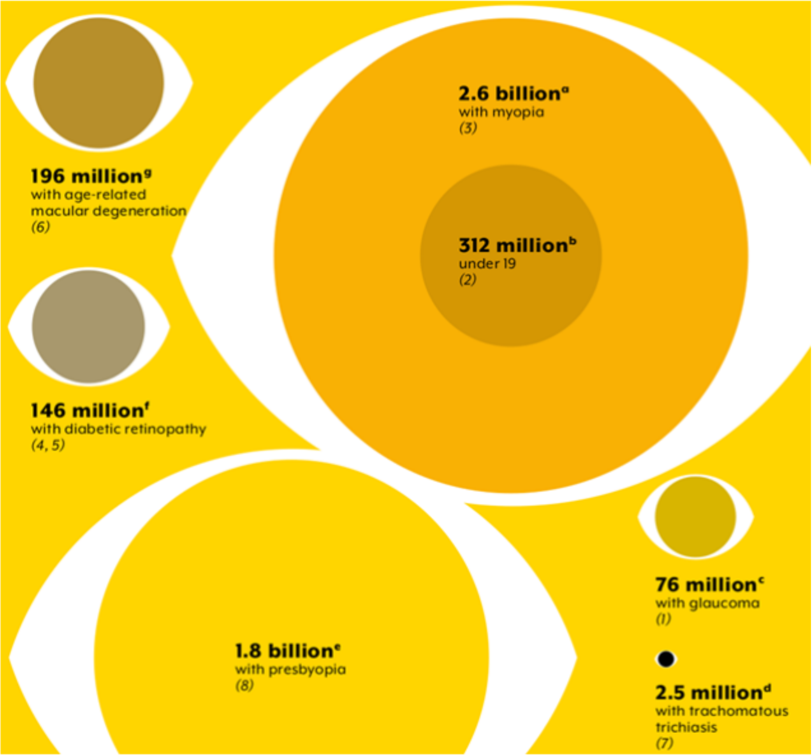


https://iris.who.int/handle/10665/328717

Trifocal intraocular lens selection: Predicting visual function from optical quality measurements. **Journal of Refractive Surgery, 39(2), 111–118.** https://doi.org/10.3928/1081597X-20221207-02 (doi.org in Bing)

Importance of the Problem

Motivation



Importance/global need

https://iris.who.int/handle/10665/328717

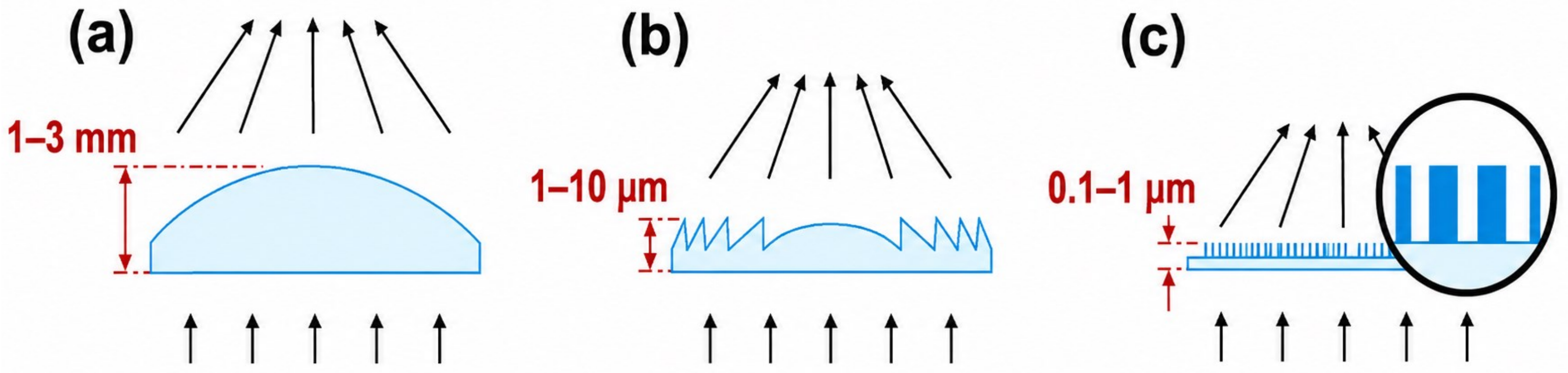


Figure 3. Compared thicknesses of a) a common lens, b) a Fresnel lens, c) a ML. (Typical values, out-of-scale.)

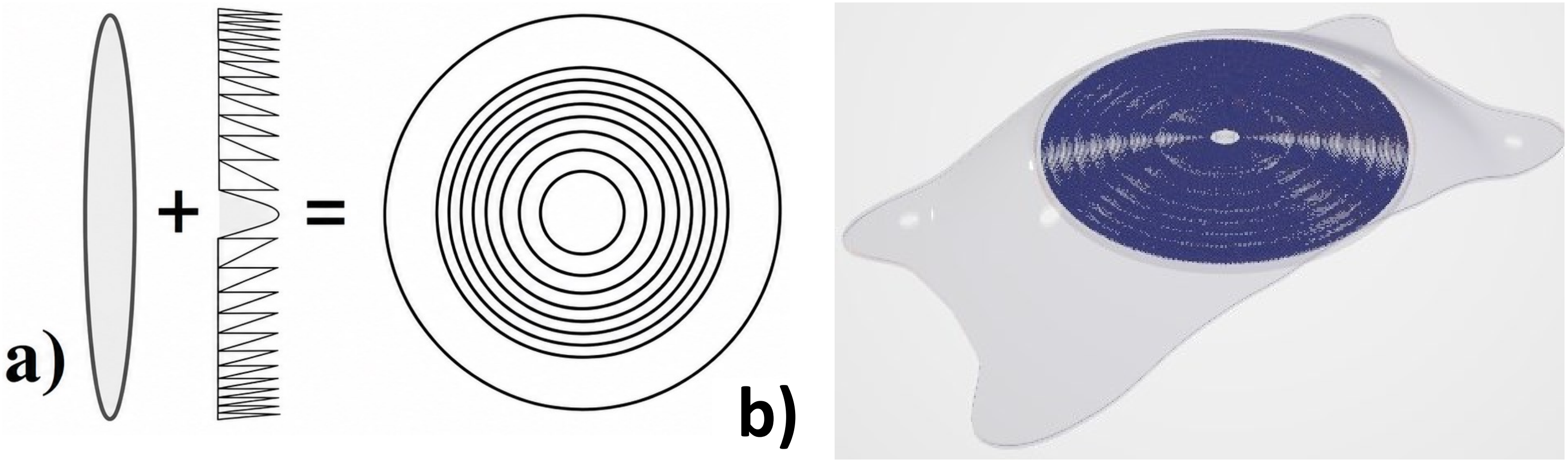
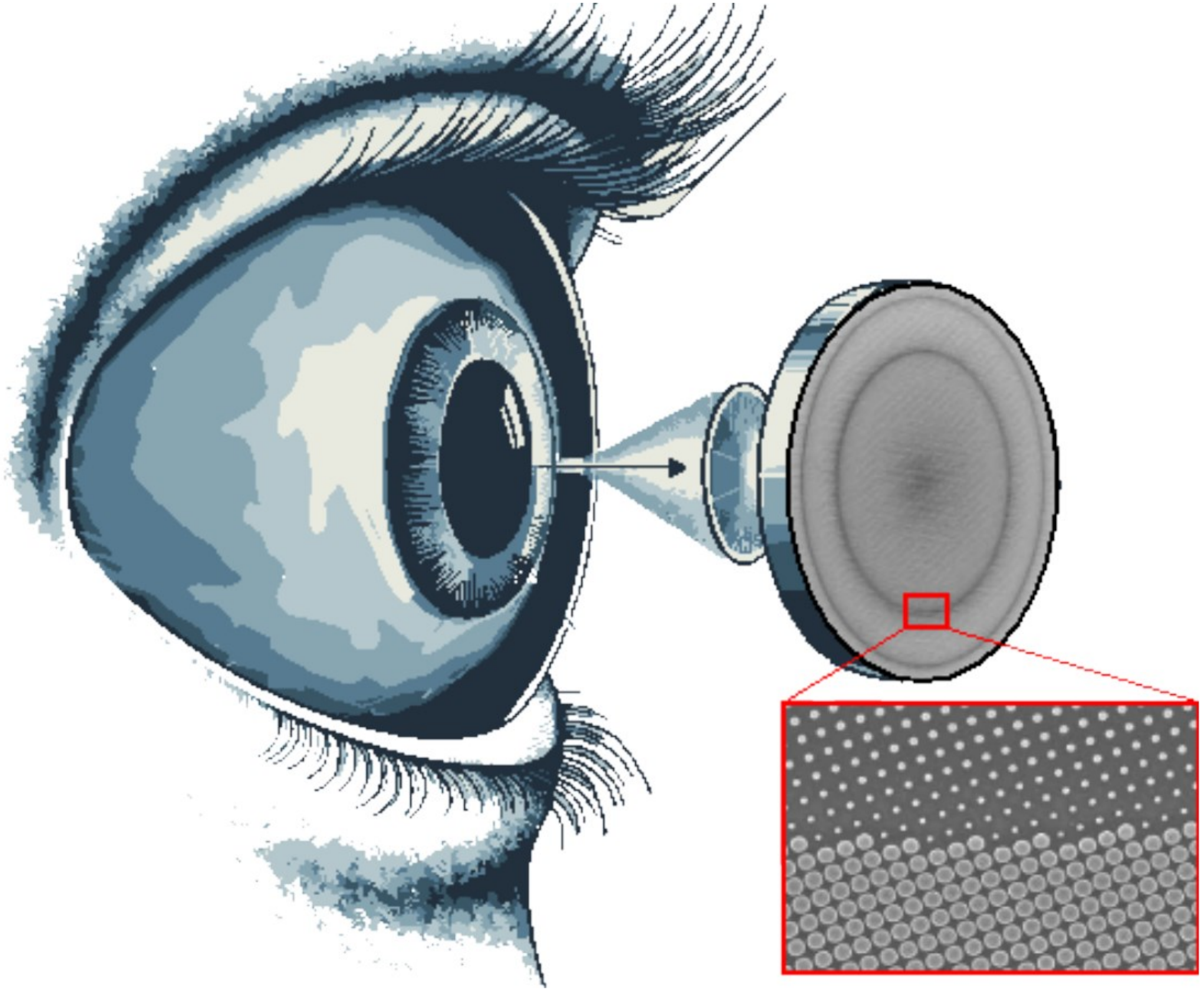


Figure 4. Multifocal diffractive IOL: a) scheme; b) actual device.

Aim of the Project

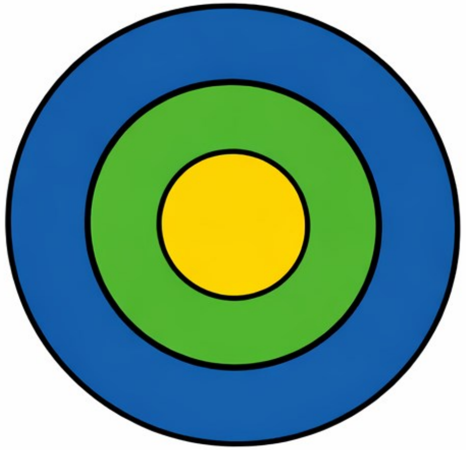
Generation of IOLs and special CLs based on the new technology of optical metasurfaces **(MSs).**

Clinical specs → Meta-IOL → Validation



Multifocal diffractive IOL concept::-
Enabling unprecedented optical power and aberrations corrections

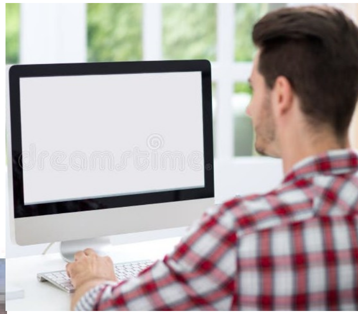
Trifocal Lens Design



Near phase focus

Intermediate phase focus

Far phase focus



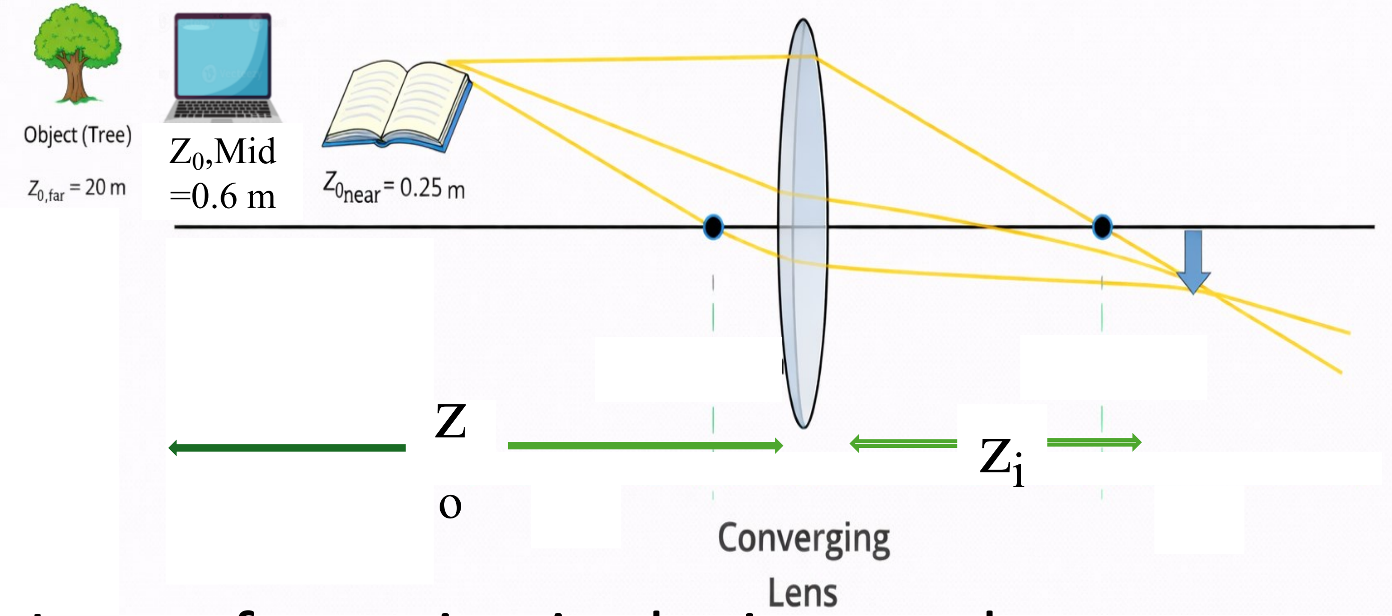
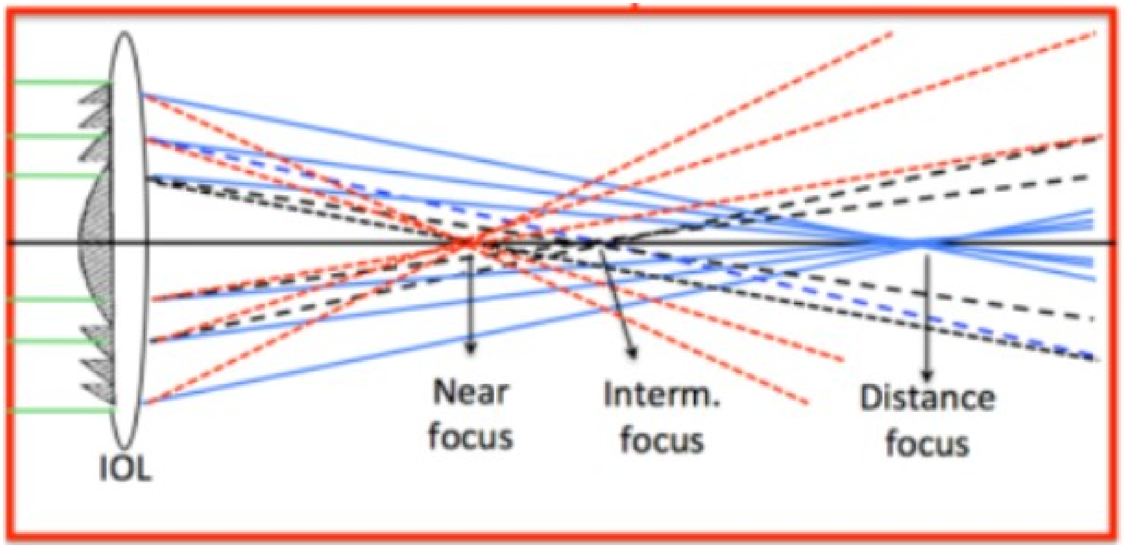


Image formation in the image plane



The three focuses at different distance

Current Status of Literature

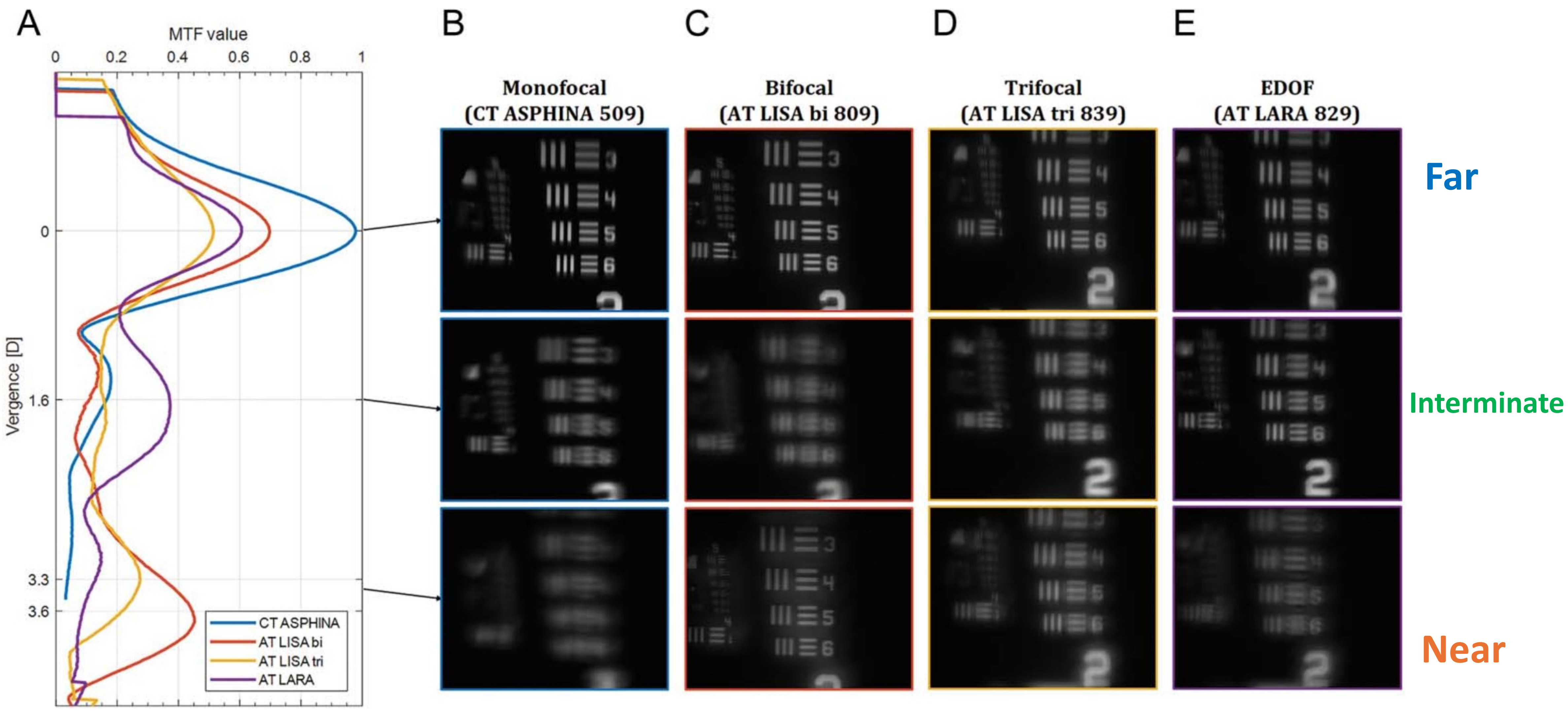
Ocular Aberrations and Measurement Techniques:

- Aberrations , spherical, coma, and astigmatism.
- Measurement techniques, aberrometry, topography, and wavefront detection.

Clinical Data on Post-Cataract Aberrations and Multifocal IOL Performance:

- Multifocal IOLs introduce **glare**, **halos**, and reduced **contrast sensitivity**.

Purpose: To evaluate and compare the optical performances of 4 different types of intraocular lenses (IOLs) in various spherical aberration (SA) conditions.



Park S., Kim M.J., Kim K.H. (2022). *In vitro optical performance of multifocal and EDoF IOLs under spherical aberration.* JCRS, 48:616–622.

Literature review: evidence base

Trifocal IOLs • optical metrics • aberrations • robustness • meta-IOL direction

What the literature defines for the project

01 Clinical need: far + intermediate + near vision

Bifocal designs leave an intermediate gap; trifocal/EDOF designs try to widen functional vision.

02 Optical quality metrics

USAF target images, PSF, through-focus MTF, MTFa/EE, and predicted visual acuity.

03 Aberration and pupil dependence

Spherical/chromatic aberration and pupil size can change MTF and retinal image quality.

04 Realistic robustness problems

Tilt, decentration, halos, glare, and contrast loss affect multifocal IOL performance.

05 Design direction

Use this evidence to set clinical targets and compare SD vs MIX before meta-IOL translation.

Take-home: literature gives the clinical target, the simulation metrics, and the gap for personalized meta-IOL design.

Representative papers reviewed

Clinically Relevant Optical Properties of Bifocal, Trifocal, and Extended Depth of Focus Intraocular Lenses

Trifocal / EDOF

Damien Gatinel, MD, PhD; Jérôme Loicq, PhD

Laboratory Evaluation of the Influence of Decentration and Pupil Size on the Optical Performance of a Monofocal, Bifocal, and Trifocal Intraocular Lens

Decentration

Tamer Tandogan, MD; Hyeck Soo Son, MD; Chul Young Choi, MD, PhD; Michael C. Knorz, MD, PhD; Gerd U. Auffarth, MD, PhD; Ramin Khoramnia, MD

In vitro optical performance of multifocal and extended depth-of-focus intraocular lenses in spherical aberration conditions

Spherical aberration

Soohyun Park, BS, Myoung Joon Kim, MD, PhD, Ki Hean Kim, PhD

Trifocal Intraocular Lens Selection: Predicting Visual Function From Optical Quality Measurements

Trifocal selection

Weijia Yan, MSc; Grzegorz Łabuz, PhD; Ramin Khoramnia, MD, PhD; Gerd U. Auffarth, MD, PhD

Optical performance of a new design of trifocal intraocular lens based on the Devil's diffractive lens

Walter D. Furlan[1], Anabel Martínez-Espert[1,*], Diego Montagud-Martínez[1,2], Vicente Ferrando[2], Salvador García-Delpech[3], and Juan A. Monsoriu[2]

New trifocal design

Computing human optical point spread functions

Andrew B. Watson NASA Ames Research Center, Moffett Field, CA, USA

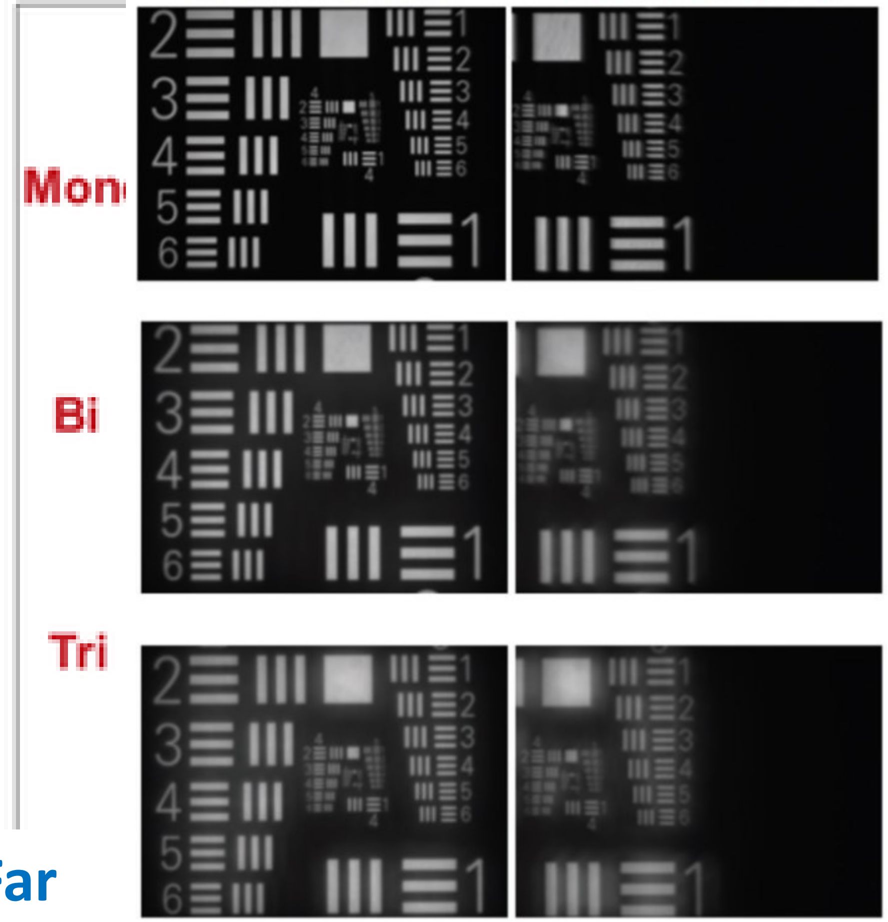
PSF / retinal image

Refs: Gatinel 2016; Tandogan 2017; Park 2022; Yan 2023; Ruiz-Alcocer 2014; Furlan et al.; Watson 2015; Armengol 2020.

Problems to solve

Tilt / decentration

0.00 mm 1.00 mm

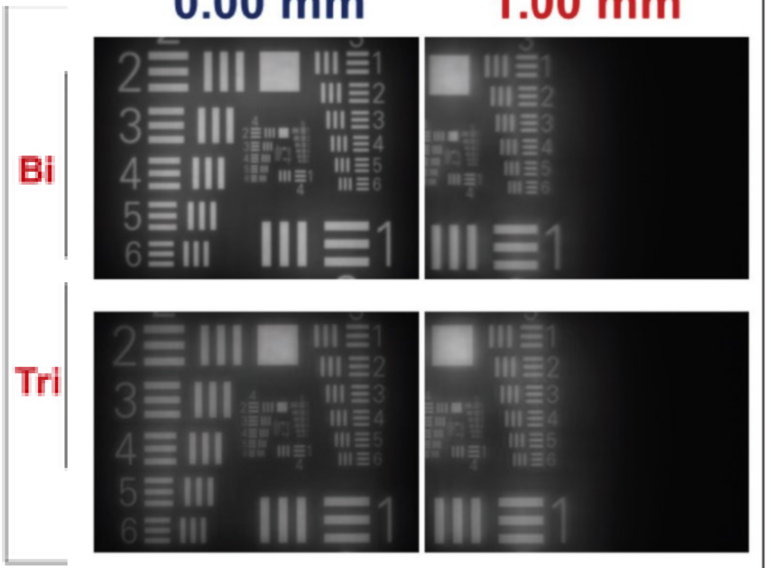


Far

Aperture 4.5 mm

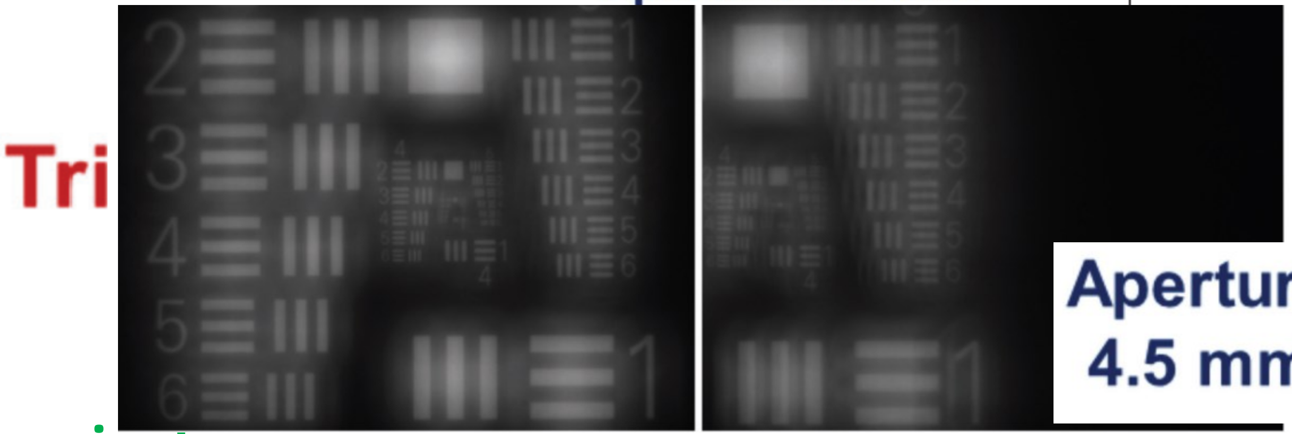
Near

0.00 mm 1.00 mm



Aperture 4.5 mm

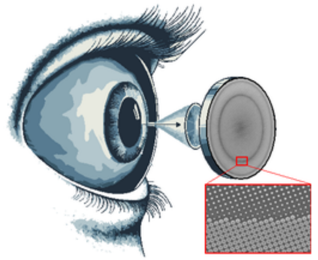
Tri



Aperture 4.5 mm

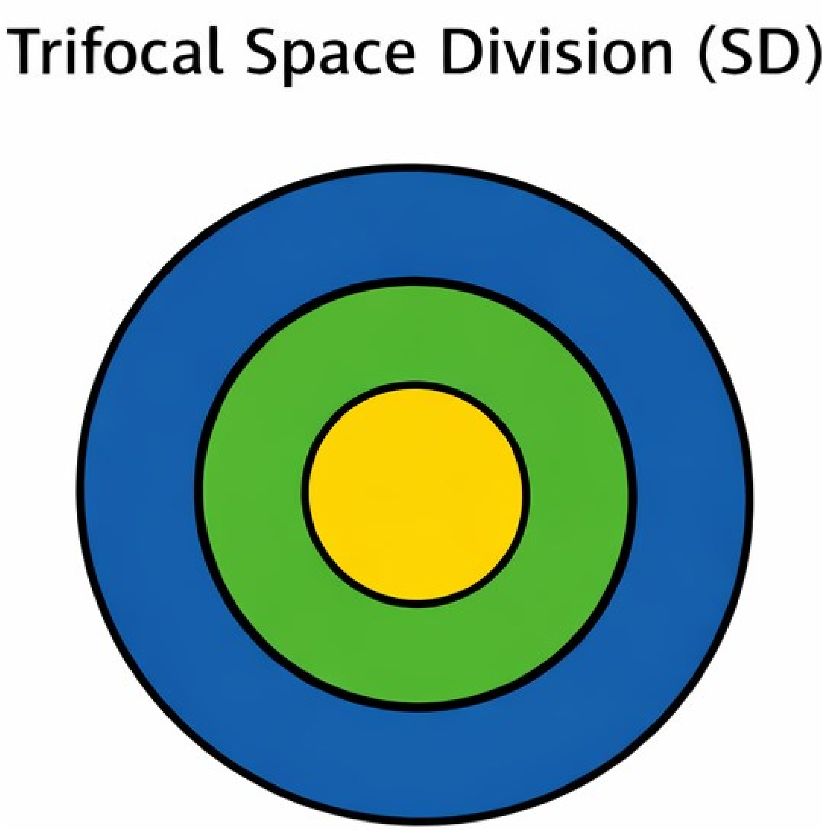
Interminate

Personalized meta-IOL



Tandoganetal.,J.Refract.Surg.2017;33(12):808–812.doi:10.3928/1081597X-20171004-02

Space Division (SD)



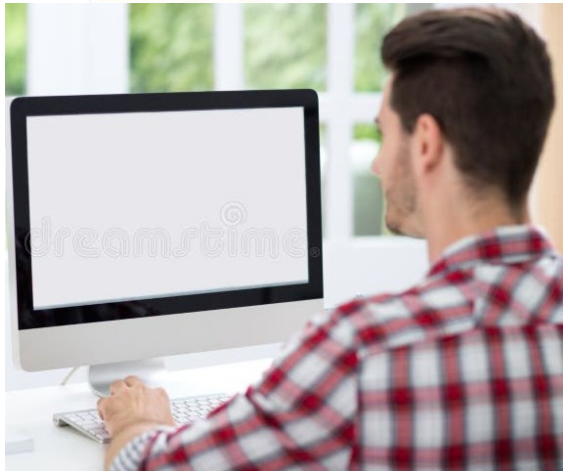
Near phase focus

Intermediate phase focus

Far phase focus

@0.3 m

@0.6 m



@20 m

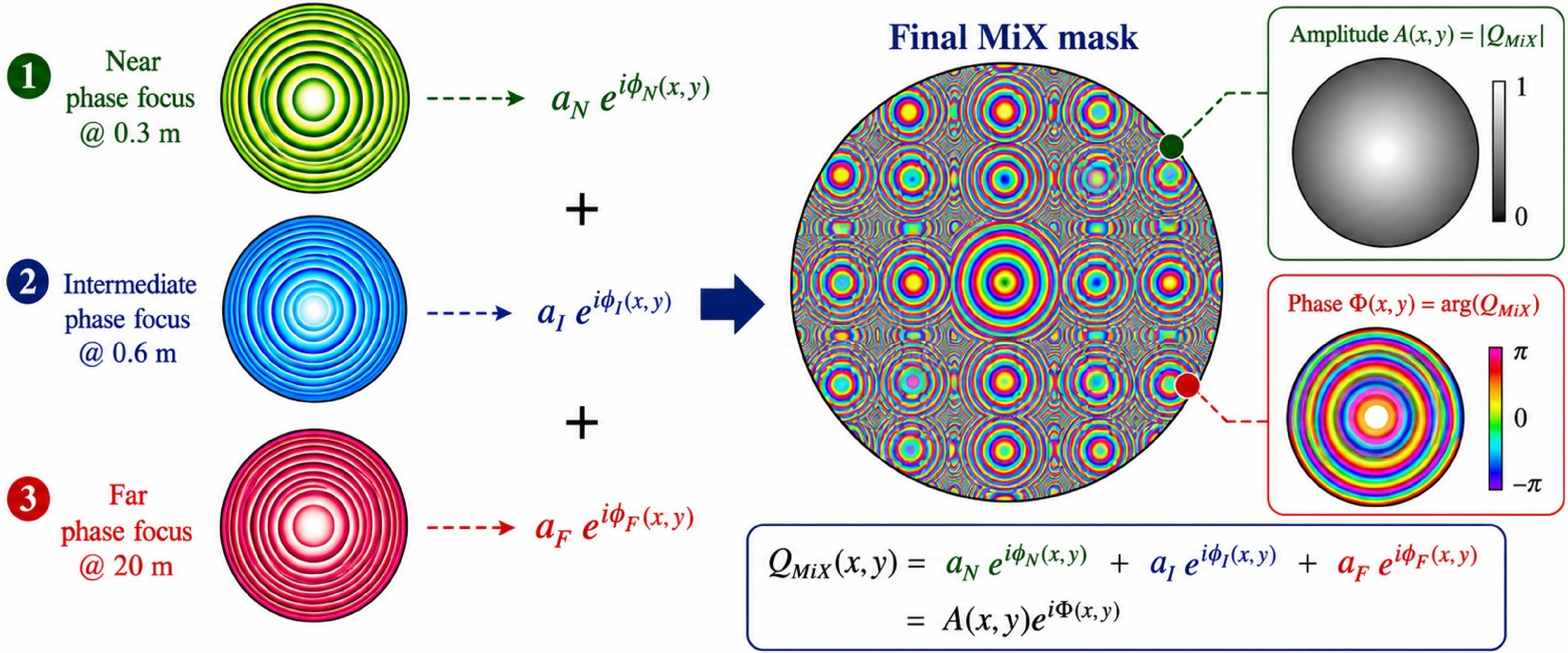
In **Space Division**, the pupil is divided into three separate spatial zones.
Each zone has **only one phase**.

$$\boxed{Q_{\mathrm{SD}}(x,y) = M_N(x,y)e^{i\phi_N(x,y)} + M_I(x,y)e^{i\phi_I(x,y)} + M_F(x,y)e^{i\phi_F(x,y)}}$$

where: $M_N + M_I + M_F = 1$

So SD is a **pure phase mask**: $|\, Q_{\mathrm{SD}} \,| = 1$ inside the aperture.

Mixed Everywhere (MiX) Approach



All three focusing phases are **coherently added** at **every aperture point**.
Unlike space-division, the aperture is **not partitioned** into separate zones.

Simulation workflow: object → retinal image

A simple optical image-processing pipeline for SD and MIX designs

INPUT

1 Object + distance
USAF image at near, intermediate, or far object distance
`I0(x0,y0)`

OPTICAL MODEL

2 Trifocal mask
Choose one optical design: Space Division or Mixed-Everywhere
`QSD or QMIX`

3 Impulse response
Calculate how the optical system responds to one point
`h = Fresnel(Q * defocus)`

QUALITY OUTPUTS

4 PSF
Convert the point response into the blur pattern
`PSF = |h|^2`

5 Retinal image
Use the PSF to form the final incoherent image on the retina
`Iret = Igeo * PSF`

6 MTF
Measure how well contrast and fine details are preserved
`MTF = |FT(PSF)|`

What the audience should remember

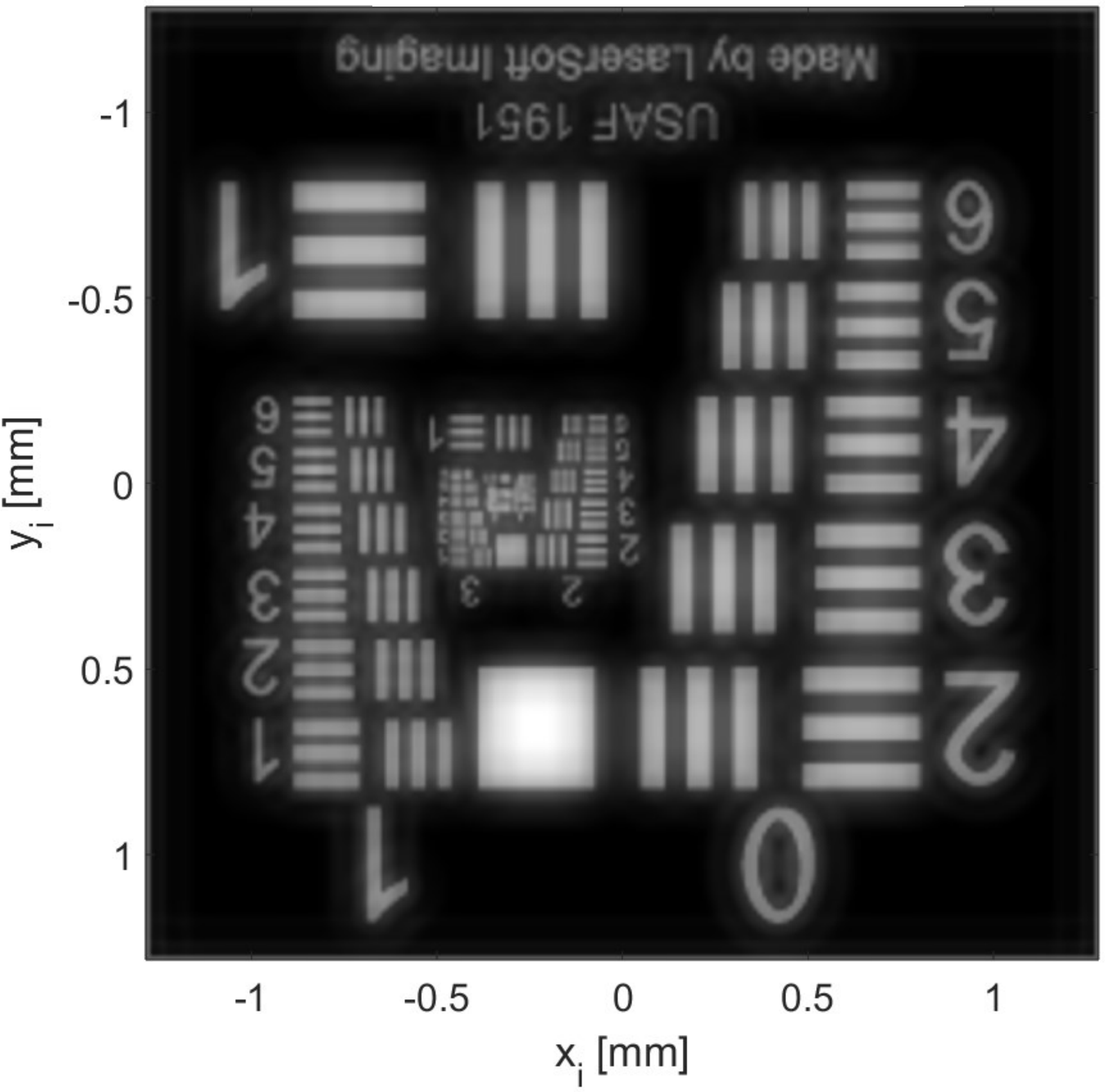
Input image → optical mask → system response → retinal image → image-quality metric

The same workflow is repeated for near, intermediate, and far cases, then SD and MIX are compared.

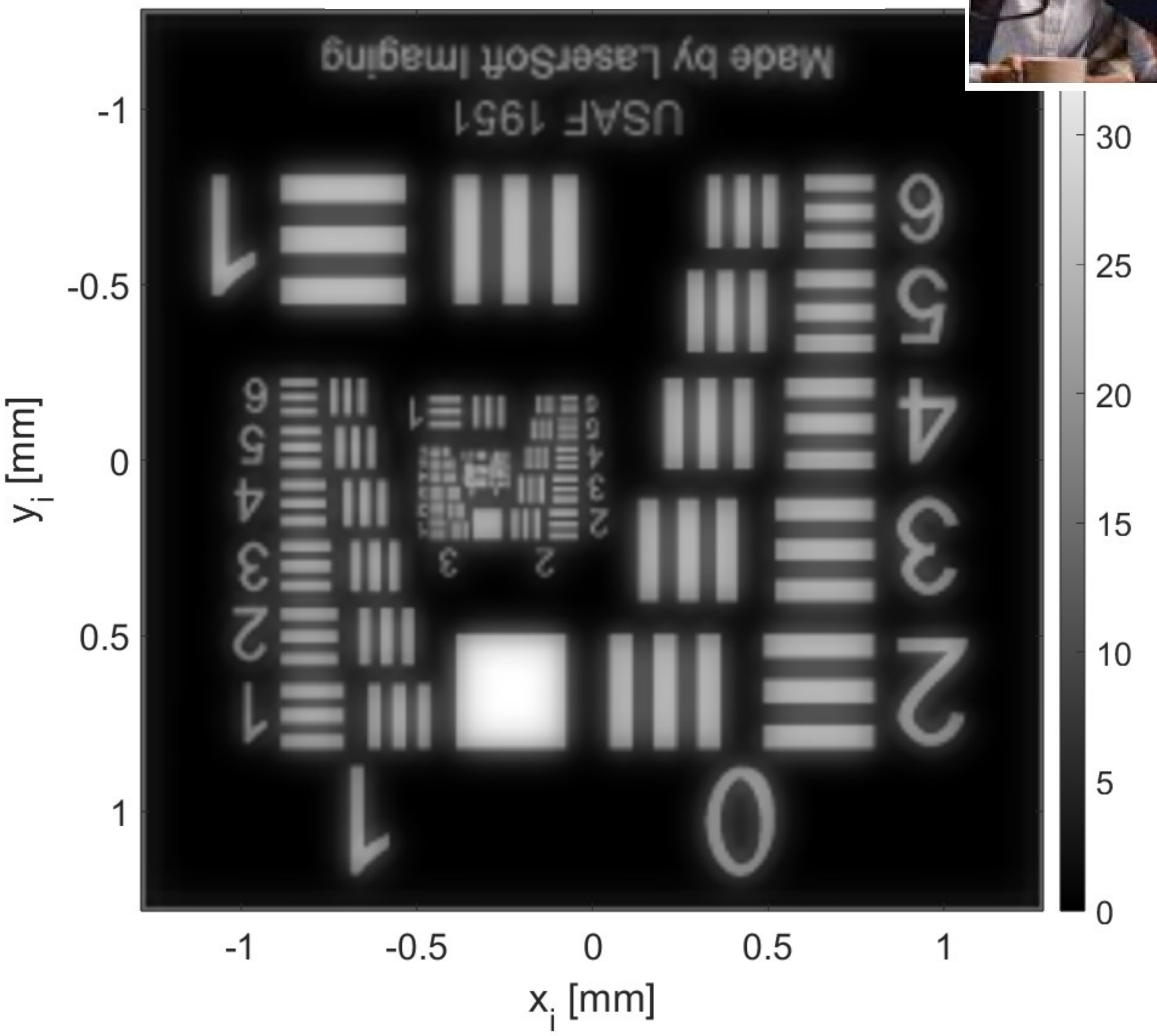
RESULTS

Trifocal retina image: Near case

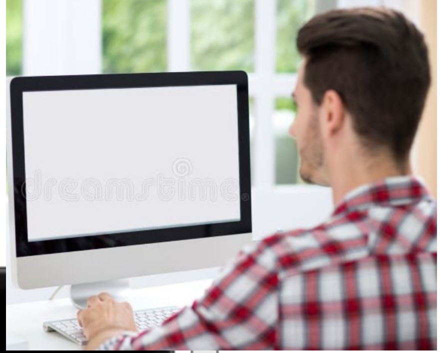
Space Division



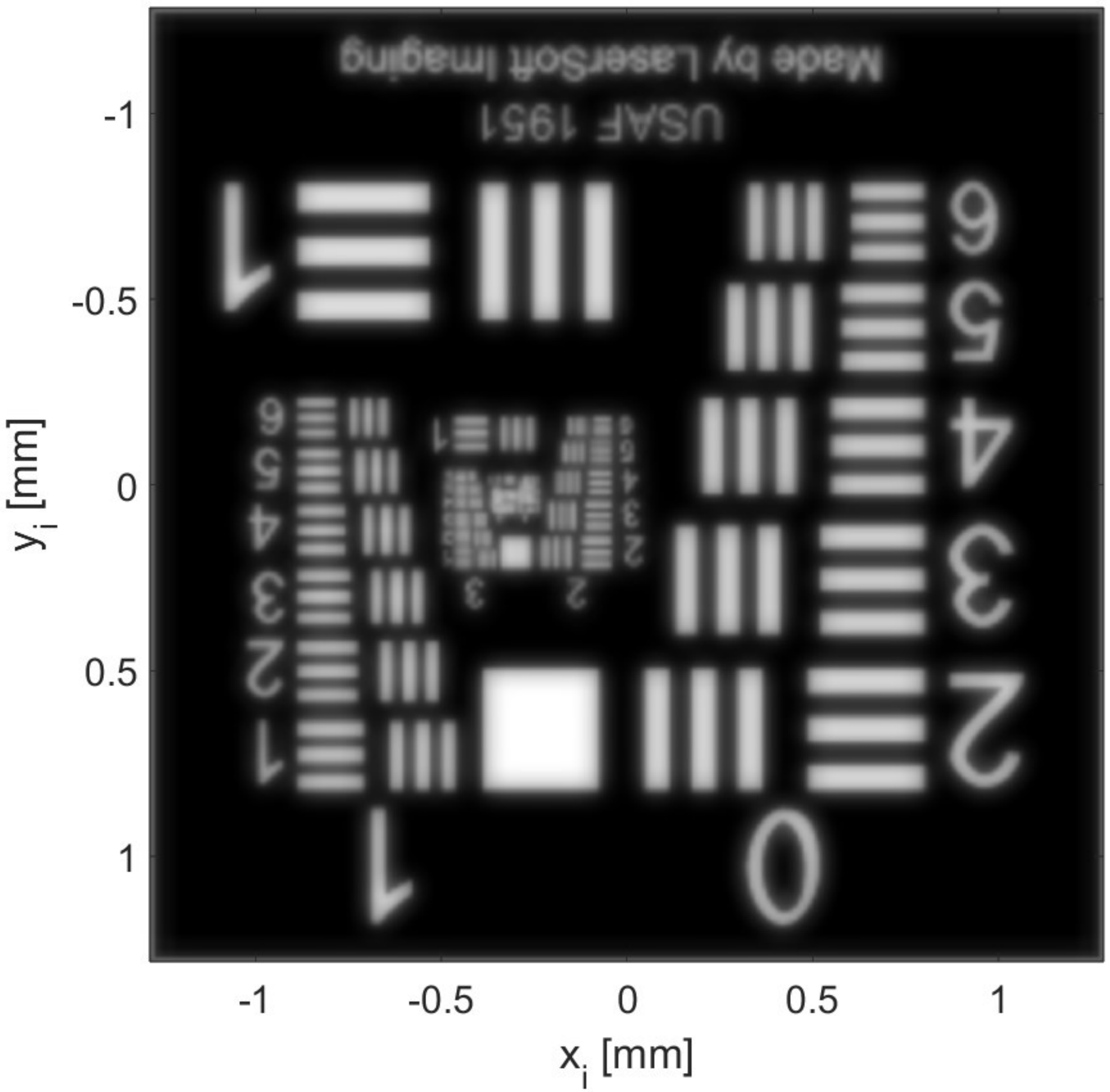
Mixed Approach



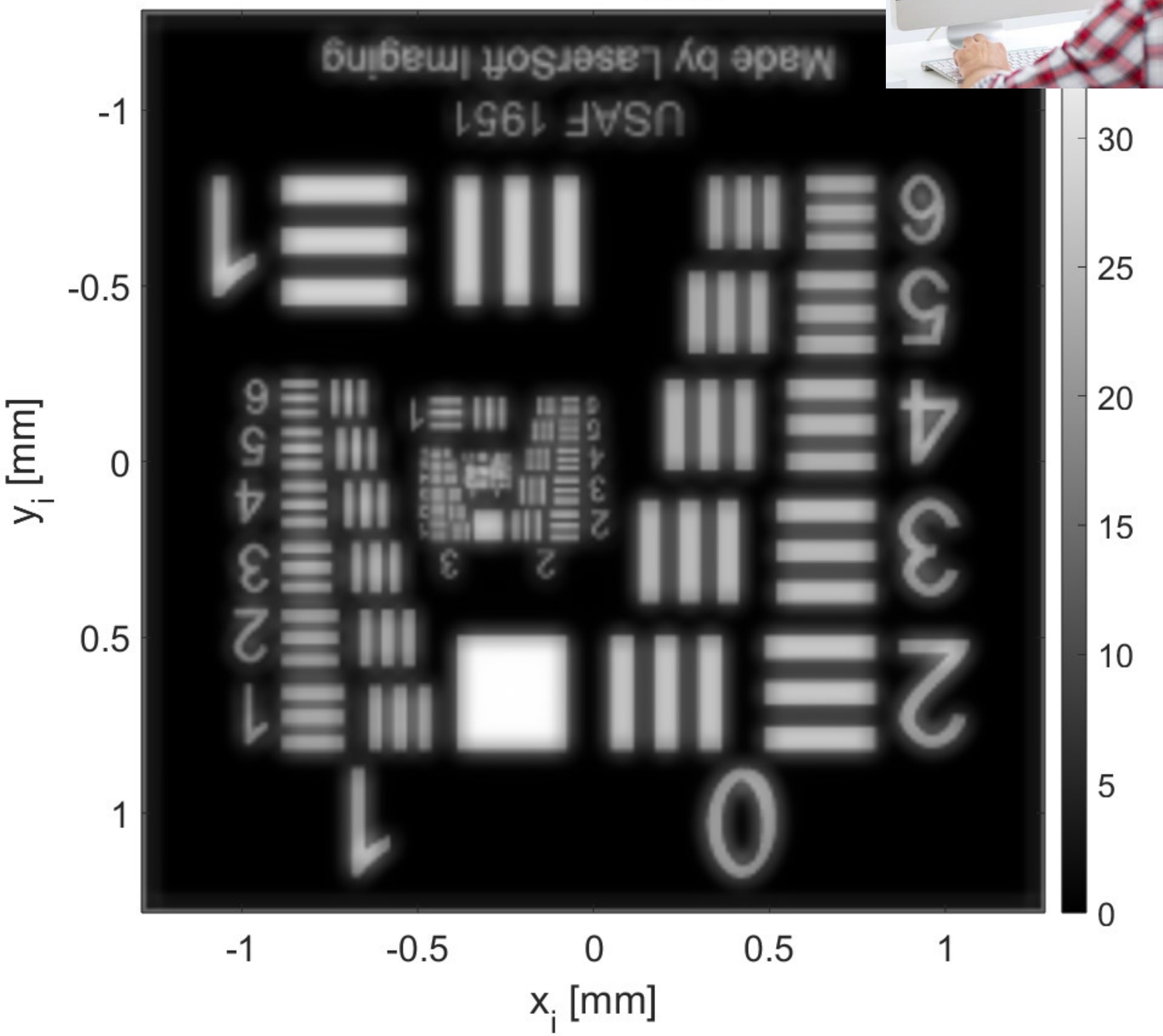
Trifocal retina image: Mid case



Space Division

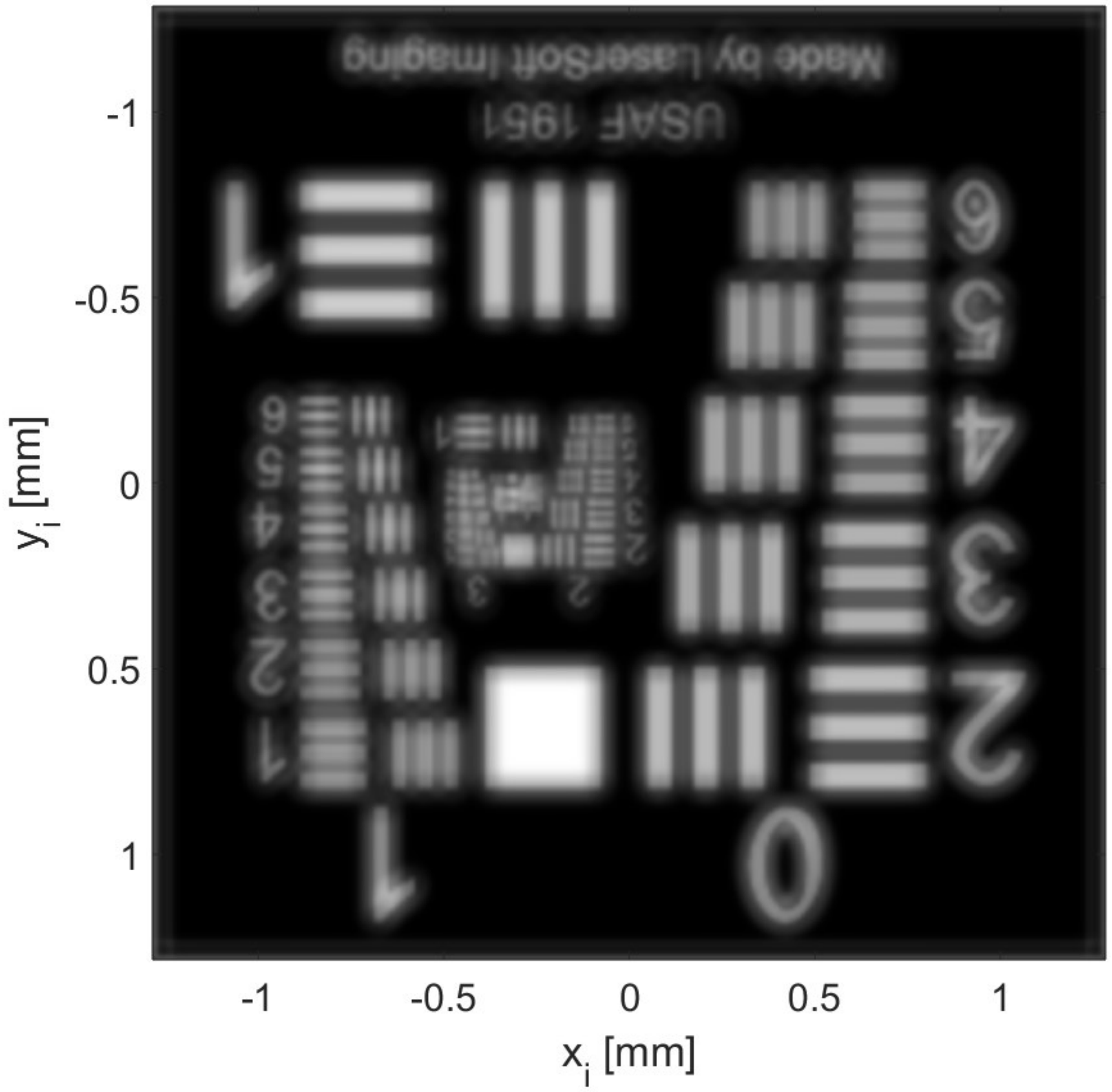


Mixed Approach

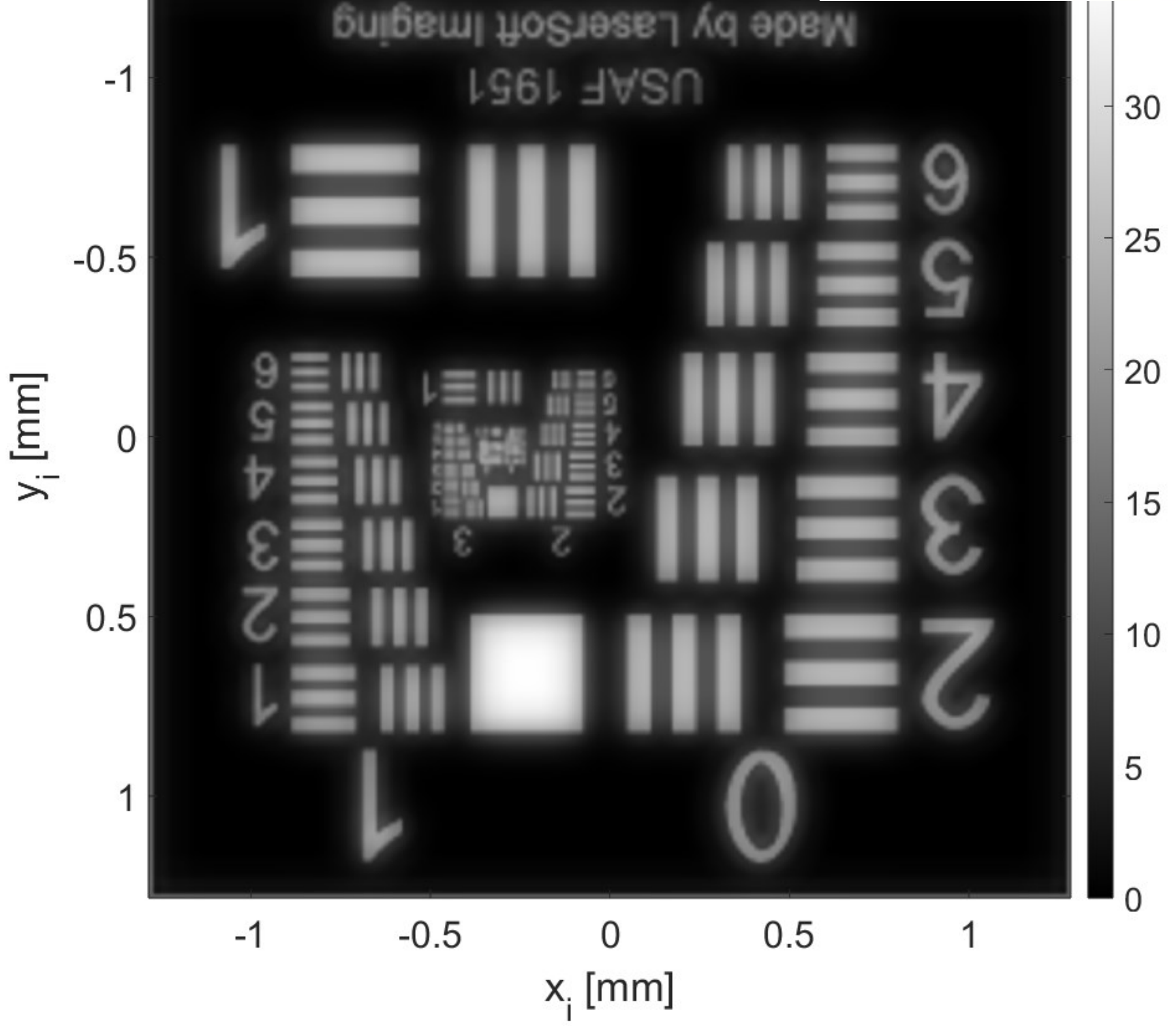


Trifocal retina image: Far case

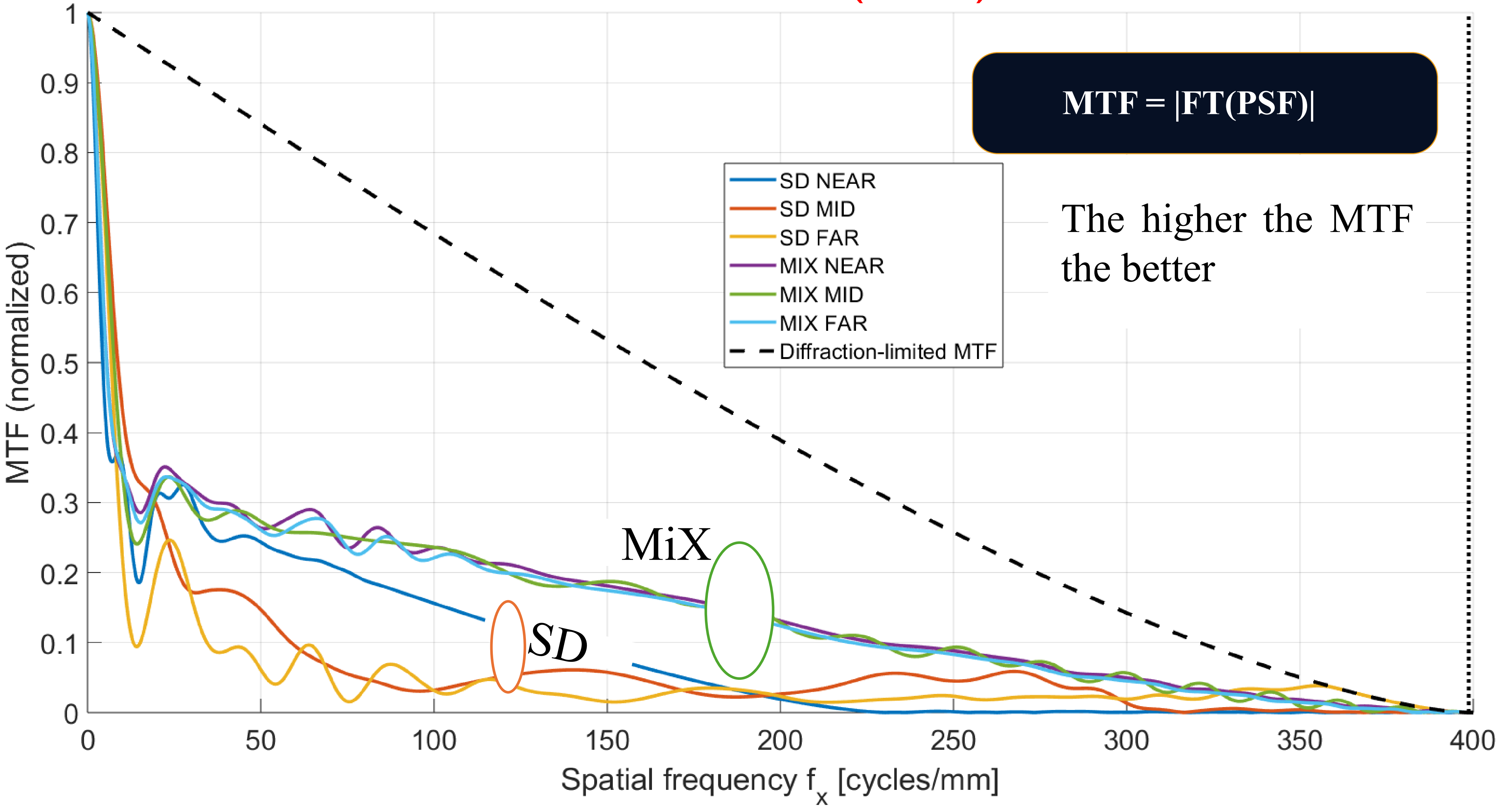
Space Division



Mixed Approach



Modulation Transfer Function (MTF) SD vs MiX



Conclusion

Space Division and Mixed-Everywhere trifocal designs were compared using retinal image simulations and MTF analysis.

The Mixed-Everywhere approach showed better image quality and contrast preservation, especially at intermediate and far vision.

Future work, Project pipeline & current status

Status: on track

Multifocal meta-IOL: from clinical needs to preclinical validation

0–6 months — **01**

Clinical specs

Completed / finalizing

Literature + patient data
Conventional trifocal model
Clinically relevant targets

6–12 months — **02**

Optical design

Next step

Meta-IOL phase design
PSF · MTF · efficiency
First TiO_2 prototypes

Year 2 — **03**

Bio-integration & feasibility studies

Collaborative exploration

Flexible support
Biocompatibility/stability
Mechanical and artificial eye evaluation

Year 3 — **04**

Preclinical Perspective

Long term objective

Retinal image quality
EDOF + residual aberrations
Translational dossier

Current focus

✓ Trifocal concept established → Manuscript framing → Translate to meta-IOL ✓ Training & seminars completed

The project is moving from a conventional trifocal model toward a realistic, preclinically validated meta-IOL.

Executed Activities & planned works

Executed activities and planned work — IAMED PhD meeting

STATUS	ACTIVITY	TIME / PERIOD	EFFORT
DONE	**English training** General English • Academic Writing • Public Speaking	Jan–12 Jun 2026	62 h
DONE	**IAMED seminars • Optics Seminars** 26 Feb • 12 Mar • 9 Apr • 30 Apr	Feb–Apr 2026	4 meetings / 9 h Optics 7 meetings / 15 h
DONE	**Conferences** ▪ Online Conference in Optics (IOCO2026) ▪ Metasurfaces Colloquium	25–27 Mar 21–24 Apr	2 events / 7 days
NEXT	**Laboratory for Modern Optics Course** Brescia	7–10 Jul 2026	12 h
NEXT	**Research work** Supervisor work + meta-IOL development	Ongoing	continuous

- **Training completed • scientific events attended**
- **Next: lab work and Meta-IOL development**

Acknowledgements

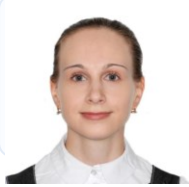
Thank you

This project is built through optics, clinical guidance and bioengineering collaboration.

Optics & metasurfaces — NORA Group

Costantino De Angelis
Supervisor · photonics & metasurfaces

Marco Gandolfi
Co-supervisor · optical modelling



Olga Sergaeva
Post-doc · optical simulations

Andrea Tognazzi
Post-doc · metasurface design

Andrea Locatelli
Full Professor · photonics

Paolo Franceschini
Post-doc · NORA Research support

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Clinical Supervision & Ophthalmology Team

Vito Romano
Supervisor · ophthalmology & cataract/IOL

Matteo Airaldi
ophthalmology

Ferdinando Giuliano
Clinical collaborator · ophthalmology

Optics ↔ Clinic ↔ Bioengineering

Thank YOU

For Your Attention!

Any Questions

Email:- t.mekonen@unibs.it

PURPOSE: To apply in vitro quality metrics to assess and compare three trifocal intraocular lenses (IOLs).

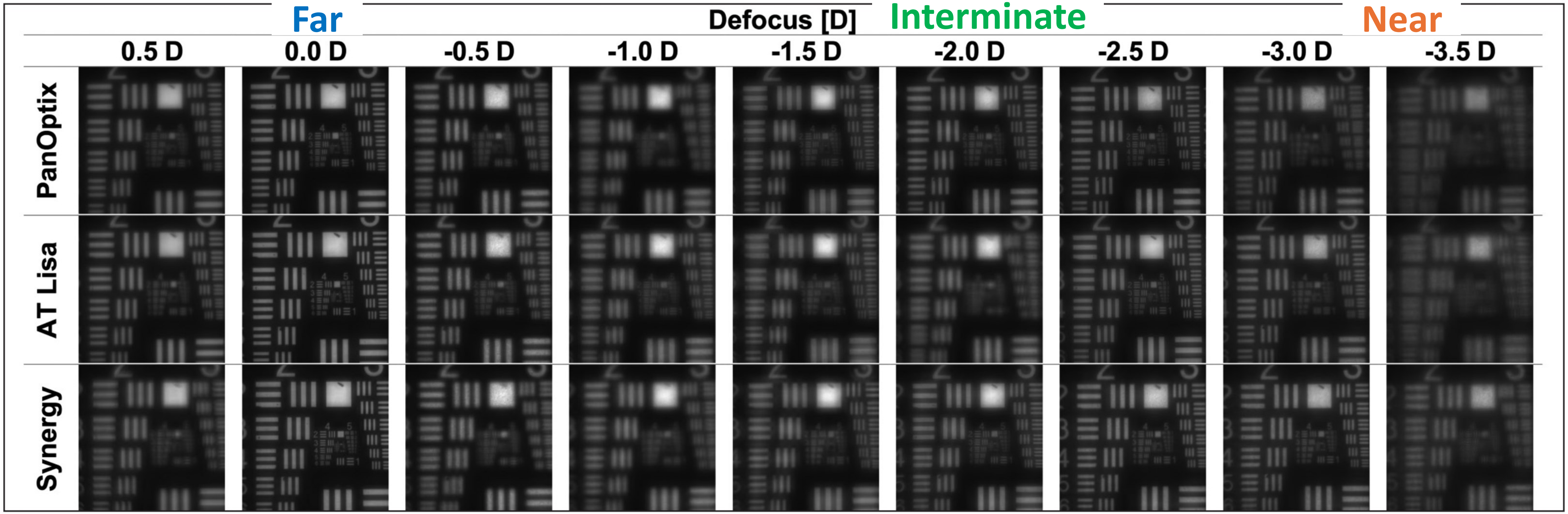
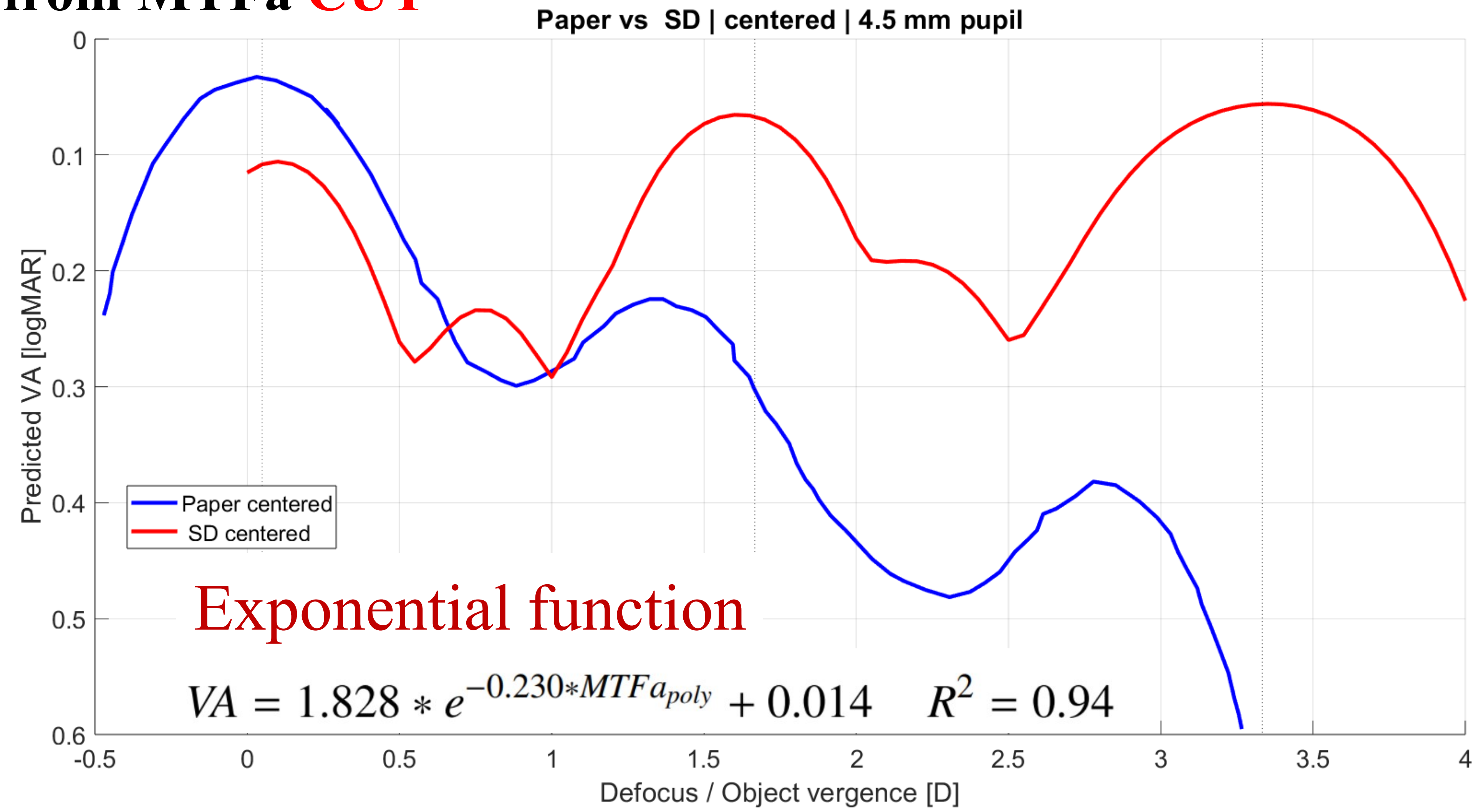


Figure C. United States Air Force target images recorded at a defocus range of +0.50 to -3.50 diopters (D) at a photopic pupil. The AT LISA tri 839MP is manufactured by Carl Zeiss Meditec AG, the AcrySof IQ PanOptix is manufactured by Alcon Laboratories, Inc, and the TECNIS Synergy is manufactured by Johnson & Johnson Vision.

Trifocal intraocular lens selection: Predicting visual function from optical quality measurements. **Journal of Refractive Surgery, 39(2), 111–118.**
https://doi.org/10.3928/1081597X-20221207-02 (doi.org in Bing)

A VA (Visual acuity) defocus curves with the Devil's MIOL Vs Our SD Design, obtained from MTFa CUT

SD VS Paper @ 4.5 mm Pupil



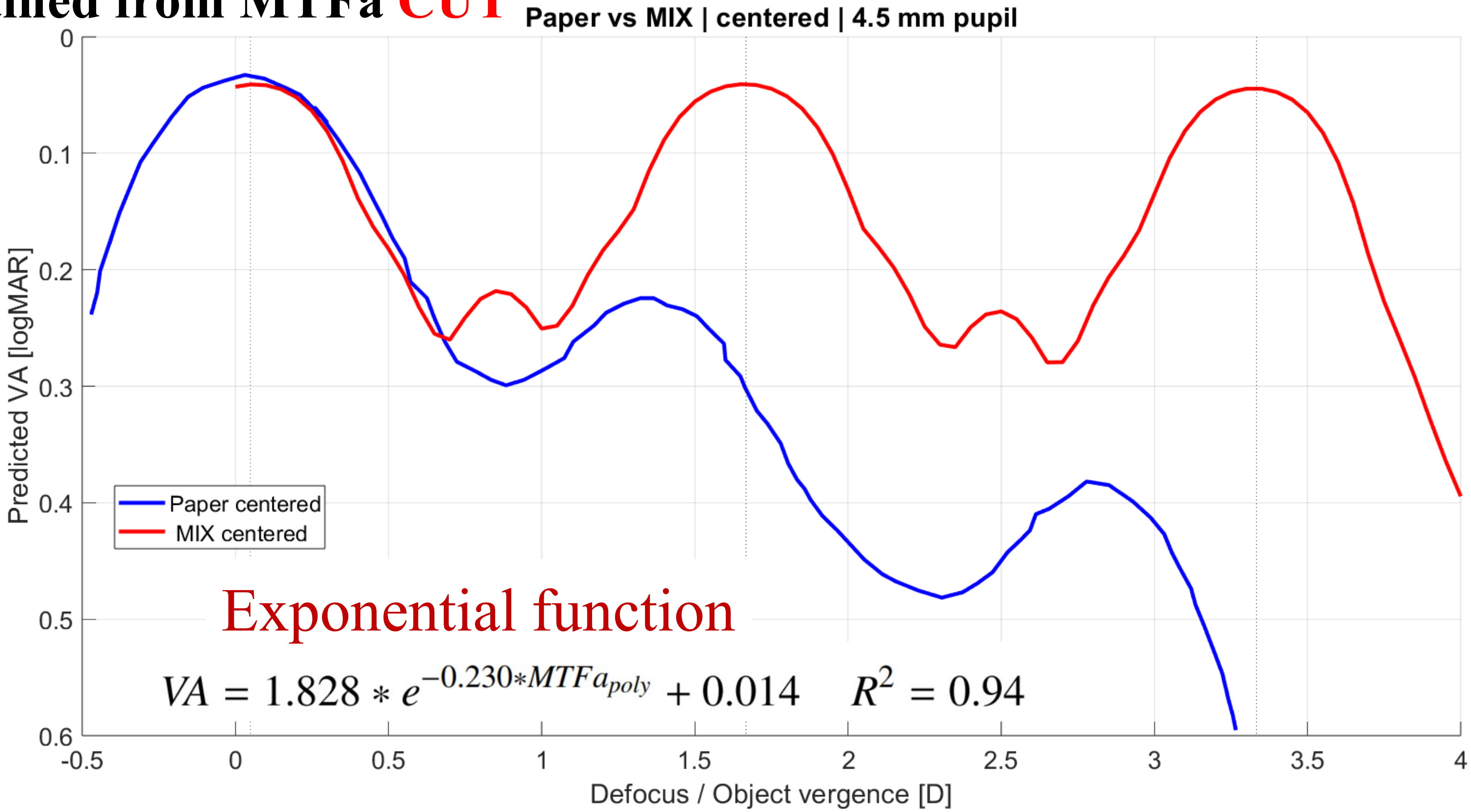
Exponential function

$$VA = 1.828 * e^{-0.230*MTFa_{poly}} + 0.014 \quad R^2 = 0.94$$

Furlan et al., "Optical performance of a new design of trifocal intraocular lens based on the Devil's diffractive lens," arXiv:2302.06996 (2023).

A VA (Visual acuity) defocus curves with the Devil's MIOL Vs Our MiX Design, obtained from MTFa CUT

MiX VS Paper @ 4.5 mm Pupil



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