Transcript of 2012 Prentice Lecture by Dr Larry Thibos

Thibos: Galileo taught us that if you want to understand the universe, you had to measure it. Nowadays we take a great deal of interest in the imperfections of the eye, because we can measure them, and because we can measure them, there's a great deal of opportunity to try and fix them.

Narrator: Drawing on his electrical engineering background and quantitative skills, Larry Thibos has focused his research efforts on improving methods for monitoring and measuring visual performance and optical quality of the eye.

[0:39]

Thibos: What you see here is what I think is the world's only two-dimensional scanning wavefront aberrometer. It was developed for the purpose of measuring optical aberrations of the eye not only along the foveal line of sight, which is what most aberrometers do, but also along multiple peripheral lines of sight. The patient sits here (indicates with yardstick) and we have a beam of light that is effectively rotated around the center of the eye's pupil – horizontally, vertically – with the central pivot point at the center of the pupil. That's what these rotating mirrors do – direct the beam of light to the center of the pupil.

[1:30]

Thibos: For the scanning wavefront aberrometer, the light comes into the pupil at the center of the pupil and rotates at different angles. The light goes in the eye, hits the retina and gets reflected back out of the eye. When the light gets reflected back out of the eye it is captured by a lenslet array to form an array of little spots. The location of those spots tells us about the aberrations in the eye.

[1:53]

Thibos: I'm hoping that it will become common practice for optometrists do a quick scan of the patient's eye and have on record the optical quality of that patient's eye over multiple lines of sight within a few seconds.

[2:11]

Thibos: In a way, we do clinical research here even though I'm not a clinician. I say that because the things we learn help clinicians to better understand what it is they are doing. We've helped improve the quality of patient care by being able to better monitor the outcome of treatments applied to eyes. The big clinical payoff in all this aberrometry is not so much in measuring the eye to build a better pair of spectacles or better contact lenses. My feeling is that the real clinical payoff is in the development of clinical ophthalmoscopes that make use of an aberrometer to measure in real time the aberrations of the patients' eye and so we can correct them and do high-resolution imaging of the eye's internal structures. That's where the payoff is.

[2:59]

Narrator: In recognition of his remarkable career devoted to improving vision and eye care through experimental research, the American Academy of Optometry proudly presents the Charles F. Prentice Medal to Dr. Larry Thibos.

[3:24] -BEGINNING OF ACCEPTANCE SPEECH

It's a good day to be a Hoosier! I'm pleased to be up here representing Indiana University (there are quite a few Hoosiers on today's program) and I'm going to be telling you a little about wavefront measurement of refractive state.

[3:38]

As you will all appreciate, no-one in the modern world of research works alone. I've had the privilege of working at Indiana University where there are many people of like mind. We have a large visual optics group at Indiana, and I can thank them all for their contributions in helping advance our program.

[4:00]

I have a long list of colleagues and co-authors to acknowledge – I was surprised myself when I starting adding them all up. They number 111 individuals in 11 countries over 40 years. There are so many I couldn't fit them all onto one slide!

[4:21]

We've also been very good in my lab at spending other people's money, so I want to thank you for your generous contributions to the National Institutes of Health (those of you who are American taxpayers) and to those of you from foreign countries in helping to support your own international agencies that support scientific research. The National Eye Institute has generously supported my entire research career at Indiana University and I'm grateful for that.

As you can see from the list of countries here, vision research is a global enterprise these days, as my colleagues live and work in many parts of the world.

However, there are three people who deserve special recognition for their persistence in teaching me the ways of the world of optometric research.

[5:03]

One of them is Prof. Ray Applegate, who unfortunately couldn't be here today because he's writing a grant application for the National Institutes of Health. Ray has taught me most of what I know about clinical optometry, and Ray has also been relentless in his demand that the work we do be clinically relevant and have practical applications.

The other person I want to mention is Prof. Arthur Bradley. Prof. Bradley is a superb experimentalist with an encyclopedic knowledge of visual science and he has taught me most of what I know about vision science. Arthur has also been an extremely loyal colleague throughout my career at Indiana University and is a very good personal friend, as is Ray.

The third person to be recognized is my wife Elspeth who has taught me everything else worth knowing. In particular, she tells me that not everyone thinks the way I do, so I appreciate that she's been able to point that out to me from time-to-time.

Our son Cameron, who is an avid reader of the New York Times and a former journalist, called me on the phone and said "Dad, you won't believe this, but Mom's picture is in the New York Times!" He sent me the link just before this meeting and, sure enough, Elspeth featured in a breaking story about the red-carpet affair going on here at the Academy meeting.

[6:24]

Some of you may have missed last night's red carpet ceremony, so I'll give you a quick update. The headine reads:

THIBOS SWEEPS AWARDS, GOES HOME WITH BOTH THE PRENTICE AND THE BABE

The text is worth reading as well:

Larry N. Thibos, mild-mannered professor at Indiana University, carried home the Academy's most prestigious prize at today's red-carpet ceremony in Phoenix, Arizona.

Thibos, of presbyopic age, said later that "Winning the prize was nice, but didn't compare with winning the besilkened babe on the red carpet!"

With typical Australian candor, Mrs T. said of her husband of 30+ years, "Before he met me, the Professor thought only wave-fronts have curvature."

[7:23]

The Prentice award is named after a founding father of professional Optometry.

When news of the Prentice award reached the midwest, I asked my students “Do you know who was Charles Prentic was”? They replied: “Of course”

delta = c times F

The man is known by his equation.

[7:39]

Sensing a teaching moment in science history, I followed up with the question: “Do you know who Albert Einstein was?”, to which they answered “Of course – he’s a square emcee”.

Get it? Einstein = mc- squared

[7:54]

And when I asked “Why is your professor receiving the Prentice medal?” their answer was: “because 3 equations are better than 1 !”

[8:08]

And when I asked, What does Prentice’s Rule have to do with wavefront refraction? their answer was: Everything!

What clever students we have at Indiana University!

[8:17]

Prentice himself would have said the same. In the second edition of his treatise on ophthalmic lenses, published in 1907, Prentice said [read quotation]:

“The prism diopter stands unchallenged in its unique ability to harmonize all of the refracting elements in the optometrical lens-case by establishing a complete and inseparable relationship between prisms and lenses”

What is this “complete and inseparable relationship” that plays such a fundamental role in optometric optics and makes Prentice’s rule even more important today than it was in Prentice’s time 100 years ago?

[8:48]

As every student of Optometry knows, Prentice’s rule describes how lenses refract rays of light. This diagram shows a bundle of parallel rays from a distant point of light, like a star in the sky, entering a lens parallel to the optical axis of the lens. For an ideal spherical lens, all of these light rays come to focus at a single point at a distance d from the lens. The symbol F in prentice’s equation is the dioptric power of the lens, which is equal to the inverse of distance d. The letter C in Prentice’s equation refers to the displacement of any incoming ray from the optical axis. If we isolate any ray for inspection we see from the geometry of right triangles that the angle Delta with which the refracted ray strikes the optical axis is equal to C/D, but since 1/D is the lens power, the angle Delta is the product of ray displacement and lens power. That is Prentice’s rule: delta = C times F.

To connect Prentice’s Rule with wavefronts, we show the continuous surface that is perpendicular to every ray of light. Now draw a tangent line to the surface at the foot of our isolated ray so we can see that the slope of the tangent line, which is also the slope of the wavefront, makes the same angle Delta with a reference plane perpendicular to the optical axis. That means that Prentice’s rule also tells us the slope of the wavefront at every point on the wavefront. Moreover, if we rearrange Prentice’s equation to form a ratio of wavefront slope Delta to the displacement C the result is 1/D, which is the vergence of the emerging ray and also the wavefront vergence.

This way of interpreting Prentice’s equation is a change in attitude that is very important. We are no longer talking about the lens itself, but the wavefront produced by that lens. This focuses our attention on the wavefront of light rather than the lens that shaped the wavefront.

Moreover, this diagram defines a perfect wavefront, the gold standard for wavefront analysis. Rearranging Prentice’s equation shows that if the ratio of Delta/C is constant then all of the rays have the same vergence, which means they all cross the optical axis at exactly the same focus point. That is what makes a wavefront perfect.

[10:38]

Of course none of us is perfect, and that goes for lenses as well. This diagram shows an aberrated lens forming an aberrated wavefront. The diagram is misleading in many ways, but is the kind of diagram seen commonly in textbooks. Some of the rays are not even in the plane of the diagram – its only our imagination that is in the plane of the diagram. The rays coming out of the plane of the diagram are called “skew rays”. Since skew rays don’t intersect the optical axis, the angle Delta is harder to envision.

Nevertheless, we can always draw a plane perpendicular to the ray (even if the ray is skew) that is tangent to the wavefront so we can measure the angle Delta. That angle tells us the slope of the wavefront at a specific point on the wavefront. If we can measure wavefront slope at many ray locations, then we can use calculus to integrate those wavefront slope data to reveal the wavefront’s shape.

This generalization of Prentice’s Rule to be a statement about wavefront slope is the foundation of modern wavefront aberrometry. The rule applies even if the wavefront is NOT a perfect sphere, so the rays do NOT have the same vergence and do NOT cross the axis at the same place.

[11:29]

Amazingly, Prentice’s rule works also for skew rays that do not intersect the optical axis, which makes it awkward to speak of vergence in the usual way.

For example, rays associated with an astigmatic wavefront rays anywhere except the principal meridia are skew to the optical axis.

In such cases, wavefront slope has two components, the usual meridional component associated with wavefront vergence and the tangential component responsible for skewness that prevents the ray from intersecting the optical axis.

Regardless of the shape of the wavefront, the meridional slope is sufficient reconstruct wavefront shape by mathematical integration. If Prentice were in the audience today, he would immediately understand the principle of modern wavefront refraction because this 21st century methodology is just a clinical application of his rule relating wavefront slope to wavefront shape.

[11:52]

Now, what does all this wavefront optics have to do with eyes? Instead of light arriving at a lens from a star, imagine a point source of light reflected from the retina and emerging from the eye’s optical system as a wavefront. If we can measure the slope of the wavefront at many points on the wavefront, then we have all of the information needed to reconstruct the shape of that wavefront.

You might have thought it possible to accomplish the same thing by measuring the intersection point of rays with the optical axis, but that is difficult for two reasons. First, it is hard to measure the crossing point of individual rays with the optical axis since the rays all get confused near the focus point. More importantly, most rays emerging from an eye don’t intersect the axis because they are aberrated so measuring the intersection point is impossible.

Instead of trying to measuring the crossing point to get ray vergence, we capture the rays as they leave the eye, while they are still well separated, and measure wavefront slope instead. This is precisely what modern wavefront aberrometers do!

[12:42]

To be fair, Prentice wasn't the first person to think this way. The basic idea for isolating rays of light to measure wavefront slopes to determine refractive errors is at least 400 years old.

The first reference I know of is Scheiner's treatise on physiological optics published in 1619. Scheiner was a contemporary of Gallileo and Kepler, and he devised a simple device now called a Scheiner Disk to isolate a pair of rays to determine the eye's refractive error.

Thomas Young 200 years later built an optometer based on Scheiner's principle which he used to measure the astigmatism of the human eye for the first time.

[13:19]

People working in other branches of optics are more familiar with Hartmann's re-discovery of Scheiner's idea in the early 20th century as a way to measure the quality of rays and lenses. In fact, Hartmann and Prentice were contemporaries so we might speculate that if they had known of each other's work, we would be celebrating the 100th birthday of wavefront aberrometry today.

This schematic diagram shows how the Scheiner-Hartmann screen isolates many individual rays simultaneously as they emerge from an eye. The intersection of each isolated ray with a light detector tells us the slope of the ray and thus the slope of the wavefront in the plane of the Hartmann screen.

[13:57]

The modern version of the Scheiner disk principle suggested by Dr. Roland Shack and Ben Platt in 1965 replaces the Hartmann screen with an array of tiny lenses which are more efficient at capturing light and focusing it onto the CCD sensor. A relay telescope images the eye's entrance pupil onto the lenslet array so that the wavefront is reproduced exactly as if the lenslets are in the plane of the entrance pupil.

This image is a schematic diagram of a modern wavefront aberrometer uisnt a laser beam to put a small spot of light on the retina. When that light reflects back out of the eye it is captured by a pair of relay lenses that focus the pupil plane onto an array of lenses that subdivide the light into many small beams. Depending on where each little beam goes, when it forms a spot image on the sensor we can figure out the slope of the wavefront over each lenslet.

Although people call this device a "Shack-Hartmann" wavefront aberrometer, we now see that the historical lineage is: Scheiner, Young, Hartmann, Prentice, Shack, Liang (who patented the idea!)

I suspect if Prentice were in the audience today, he would immediately understand the principle of modern wavefront aberrometry because this 21st century methodology is just a clinical application of his fundamental equation for specifying aberrations of an optical system as deviations of wavefront slope.

[15:00]

Measuring wavefront shape opens up a whole new world of wavefront aberrometry: the systemmatic classification of refractive errors according to shape. Fundamental wavefront shapes can be classified systematically using Zernike polynomials. Shapes above the red line are the stuff of 20th century optometry: focus errors associated with myopia and hyperopia and astigmatic errors.

Below the line are many more aberrations that are now accessible in the 21 century thanks to wavefront technology. This example includes just two shapes: coma and trefoils, but in fact there are many more shapes known to mathematicians as Zernike polynomials.

[15:37]

Zernike was a very famous scientist who won the Nobel prize for his invention of phase microscopy. He needed some new functions of this kind so he invented them for his microscopy work and when he was finished he kindly donated them to vision science for describing the optical properties of eyes.

The basic idea is to measure the shape of the wavefront reflected from and eye and then mathematically decompose that wavefront into a weighted sum of these basic shapes.

The first 21 Zernike basis functions, or “modes” as they are often called, are shown in this table. The Zernike table is best viewed as a pyramid., rather like the periodic table of the elements. Each row in the pyramid corresponds to a given order of the polynomial component of the function and each column corresponds to a different meridional frequency of the harmonic component.

The six wavefronts above the red line are the basis of 20th century optometry whereas the shapes below the line represent the expanded scope of optometry into the 21st century.

Clearly the power vector parameters M, J0 & J45 are history! They belong to the 20th century before we learned about Zernike and his lovely polynomials.

[16:32]

That is a heavy dose of optical theory to swallow so early in the morning. I apologize for making you think so hard, so I suggest a 5th inning stretch to explore a bit of optical origami. As you have seen from some of my diagrams, optics is 3-dimensional topic and the problem with most textbooks is they contain only 2-dimensional drawings. What is needed is a textbook like a child's storybook so when you open the book up pops Cinderella's castle!

I use a much simpler foldout origami when teaching students about the geometry of rays and wavefronts, which everyone received at today's ceremony.

Follow the instructions to fold the airplane to reveal the optical axis, the chief ray connecting pupil center to an object point, the meridional plane, the sagittal plane, and the AIRPLANE!

[For those members of the audience too mature for such frivolity, take it home and fly it in the privacy of your back yard ☺]

[18:22]

Back to my story. Looking back in time, I would say 1997 was the year our mindset was changed by wavefront aberrometry. That was the year OVS published a feature issue highlighting exploratory work being done using the new wavefront concept for describing the optical aberrations of the eye.

I wrote an editorial for that feature issue entitled "The New Visual Optics" which said, in part,

"Contemporary visual optics research is changing our mindset, our way of thinking about the optical system of the eye, and in the process is redefining the field of visual optics. All of the eye's optical imperfections will one day be represented comprehensively by a two dimensional map in the plane of the pupil. This pupil map will look much like the corneal topographic maps currently sued to describe the shape of the corneal surface. Interpretation of the two maps will be quite different, however, because the pupil map describes how wavefronts entering the eye from each point in the visual world become distorted from the perfect spherical shape needed to form the ideal retinal image".

[19:41]

The future arrived much sooner than anyone anticipated. Just 3 years after that editorial, the modern era of wavefront aberrometry began with the birth of the 21st century and the introduction of the first commercial aberrometer based on the Hartmann-Shack wavefront sensor in 2000 for performing wavefront refraction. We obtained one of the first units off the assembly line, which happened to have serial #007, and our very own Bond Girl, Xu Cheng, MD was the first person at Indiana to use the new instrument in a clinical setting.

This introduction of aberrometry technology also introduced a change in attitude: Now, higher order aberrations are no longer a nuisance to be avoided, we are going to take them into account when prescribing the best possible correcting lens. We would do this on the basis of a key principle for wavefront refraction: the best prescription is the one that optimizes retinal image quality.

But how can the clinician know that image quality is optimized when the only person in the world who can see the retinal image is the patient. The clinician can't look inside the eye to see if the image is well focused, so how can she know that image quality has been maximized by correcting lenses? The answer is that we can calculate the retinal image! That was one of the main motivations for measuring the eye's aberrations.

[21:12]

The wavefront aberration map is sufficient to enable an accurate calculation of retinal images, including the effects of diffraction and interference, using the principles of physical optics.

Thus, by measuring the wavefront aberrations of an eye we can use math to compute the retinal image of a single point of light. Since any object in the world is a collection of point sources, each of which is blurred the same way, we can add the superimposed images of all the points (a mathematical calculation called convolution) to see the retinal image of anything, for example an eye chart. For the first time we can give the clinician a tool that will give some insight into what the patient has to deal with when being asked to say which lens is better, #1 or #2!

[21:54]

Given this ability to compute images from wavefront measurements, we can now address the simplest, and most fundamental of optometric questions: Where is the far-point of an aberrated eye?

Our answer is that the far-point is where the object needs to be placed to optimize the quality of the retinal image. But even for a simple point of light the answer isn't obvious since different rays come to a focus at different distances.

For example, for a relaxed eye with positive spherical aberration, if we put the object in the plane of paraxial focus, the image is clearer and sharper but has lower contrast. Compare that situation with putting the object in the plane of marginal focus, where the image is darker with more contrast, but is not as legible or sharp.

By studying these aberrations we can begin to understand the optical explanation for the common clinical experience in which patients describe the eye chart as sharper or darker and why that matters for reading the chart.

[22:53]

This wavefront analysis helps us understand that there is no single true answer to the Optometrist's persistent question, “which is better?”, because many criteria (besides “sharper” or “darker”) for judging image quality are possible.

For example, the patient may be judging perceived quality based on some internal notion of personal aesthetics, a sense of beauty that makes one corrective lens preferable to another. Or quality may be based on the fidelity of the image, whether it meets some expectation or Platonic notion of what the object ought to look like. These are internal, subjective criteria that are hard to standardize for reliable and consistent use in a scientific or clinical setting.

To approach the problem scientifically it is helpful define functional optical quality in terms of measureable visual performance (criterion #3).

[23:44]

This notion of objectifying image quality leads to the formulation of a fundamental hypothesis that links the world of the psyche (mind) to the physical world of observable events. That linking hypothesis is:

Better performance indicates better images.

Conversely, better images yield better visual performance.

With that simple rule in place, it becomes possible to do objective refraction with a wavefront aberrometer.

[24:17]

A scientific paradigm for deciding which correcting lens is better begins by using the wavefront map to calculate the retinal image of a single point of light (called the point-spread function). The image of a point is typically too complicated for direct comparison, but we can reduce it to a single number using an image-quality calculator and use that number to decide which correcting lens is optimum.

One of our favorite metrics of image quality is called the Visual Strehl ratio, which tells us how strong the retinal response will be for this corrected eye compared to the optically perfect eye.

[24:50]

To summarize the process of wavefront refraction. the goal is to find the correcting lens that maximizes the quality of the retinal image.

Conceptually, the idea is to have a mini-optometrist inside the eye to assess retinal image quality using the image quality calculator. A virtual lens is then adjusted by mathematically adding a spherical wavefront or a sphero-cylindrical wavefront to the eye's wavefront in order to maximize the quality of the computed retinal image.

[25:33]

With a small step of imagination it becomes clear how to broaden the application of wavefront technology to not only determine refractive error, but to also determine the refractive state of an aberrated, accommodating eye.

All ocular aberrations change when crystalline lens accommodates, but the primary change is for Zernike defocus.

[26:05]

Recall the earlier discussion of the optimum focus plane of an eye with positive spherical aberration as shown in the top panel. When eyes accommodate to near targets, spherical aberration typically changes sign to become negative as shown in the bottom panel. So instead of the focus plane for paraxial rays being further from the eye, it is closer to the eye. That expands the range of accommodation if the goal is to produce a sharper image, but compresses the range of accommodation if the goal is to produce an image with maximum contrast. We wouldn't have been led to that insight if we hadn't taken aberrations into account when examining retinal image quality.

[26:30]

Now we have a method for computing the refractive state of the accommodating eye. The patient views a stimulus that evokes accommodation while the clinician simultaneously measures the eye's wavefront aberration and measures image quality. The question is: was the target in the optimum location? Or would retinal image quality have been greater if the target were slightly closer or further away? If image quality can be improved by defocusing the measured wavefront, that indicates the presence of an accommodative error that can be quantified as the difference between the optimum target vergence and the actual target vergence.

[26:58]

Given this change in mindset about refractive state and how it changes with accommodation, a new perspective emerges on many current issues in accommodation research.

For example,

Is retinal image quality maximum for all states of accommodation? Or are we all laggards who don't accommodate enough to optimize the quality of our retinal images?

How do changes in higher order aberrations and pupil size during accommodation affect refractive state? That's a rather radical idea: a lot of people don't think the pupil has anything to do with refractive state; refractive state is determined by the crystalline lens. From a wavefront perspective, the pupil becomes a player.

How do age-related changes in accommodation affect retinal image quality? That question is relevant to understanding the visual consequences of presbyopia.

Do presbyopia therapies work? If not, why not?

[27:46]

Wavefront aberrometry is everywhere! The future has arrived.

Today I've had time to comment only on objective refraction, and the measurement of refractive state during accommodation.

In addition, wavefront technology is being used to study tear film optics and the ocular surface

Wavefront sensors are the key component of adaptive optics systems for high-resolution imaging of the fundus.

Wavefront aberrometers help assess treatment strategies for correcting, or exploiting, higher order aberrations.

Wavefront ideas may even help unlock the mysteries of myopia development by revealing the optical conditions that control ocular growth.

[28:29]

Finish with a philosophical note on the continuing importance of visual optics research to optometry

"Visual optics is the heart of optometry, but in the grand scheme of modern science visual optics stands as the fourth branch of optics, the science of light and images. The other three branches of geometrical, physical, and quantum optics all deal with the physical issues of how light propagates, interacts with matter, and forms images independently of eyes or vision. Visual optics, on the other hand, not only recognizes the role of the eye and vision in optics, it makes that role central. Thus, visual optics transforms traditional optics, which operates in the theoretical and physical domains, into the domain of human reality, the eye, and visual perception. Through this transformation the science of visual optics makes its greatest contributions to mankind, for we are the ultimate consumers of images, our eyes and brains give meaning to light.”

In as similar way, …

I believe the Academy’ primary mission is to give voice to optometric research. In so doing the Academy makes its greatest contribution, by way of the practitioner, to the public’s well being.

Thank you for the award and thank you for being here today to share it with me.