From Unseen to Seen: Tackling the Global Burden of Uncorrected Refractive Errors

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Abstract

Worldwide, more than one billion people suffer from poor vision because they do not have the eyeglasses they need. Their uncorrected refractive errors are a major cause of global disability and drastically reduce productivity, educational opportunities, and overall quality of life. The problem persists most prevalently in low-resource settings, even though prescription eyeglasses serve as a simple, effective, and largely affordable solution. In this review, we discuss barriers to obtaining, and approaches for providing, refractive eye care. We also highlight emerging technologies that are being developed to increase the accessibility of eye care. Finally, we describe opportunities that exist for engineers to develop new solutions to positively impact the diagnosis and treatment of correctable refractive errors in low-resource settings.

Contents

1. INTRODUCTION 132
2. EPIDEMIOLOGY 133
   2.1. Prevalence of Refractive Errors 133
   2.2. Prevalence of Presbyopia 134
   2.3. Prevalence of Uncorrected Refractive Errors and Presbyopia 134
   2.4. Global Impact of Visual Impairment Due to Uncorrected Refractive Errors ... 135
3. BARRIERS TO CORRECTING REFRACTIVE ERRORS 136
4. EYE-CARE DEPLOYMENT 137
5. ESTABLISHED METHODS FOR MEASURING REFRACTIVE ERRORS 138
   5.1. Retinoscopy 139
   5.2. Autorefractors 139
   5.3. Trial Lenses 140
6. EMERGING METHODS FOR MEASURING REFRACTIVE ERRORS 141
   6.1. Self-Refraction by Adjustable Lenses 141
   6.2. Subjective Refraction with Scheiner's Principle 144
   6.3. Photorefraction 145
   6.4. Wavefront Aberrometry 145
7. REFRACTIVE ERROR CORRECTION 146
8. CHALLENGES AND FUTURE PROPOSALS 146

1. INTRODUCTION

A large portion of the global population suffers from poor vision that can be corrected with eyeglasses. These uncorrected refractive errors (URE) are the cause of debilitating vision (visual impairment) for over 100 million people worldwide (1–3), and the total population who would benefit from eyeglasses is expected to be much larger, likely over 1 billion people (4–7).

In a perfect eye (emmetropia), light from a distant source is focused to a small point on the retina, resulting in sharp distant vision. Refractive errors lead to poor focusing and typically refer to hyperopia (farsightedness), myopia (nearsightedness), or astigmatism (asymmetrical focusing) (see **Figure 1**). Left uncorrected, refractive errors can result in poor vision and even blindness.

Fortunately, refractive errors are easy to treat, requiring only a pair of eyeglasses, the prescription for which can be determined from a simple eye exam. Not only that, but owing to the relatively low cost of eyeglasses and the significant economic costs arising from the loss of productivity that accompanies URE, refractive eye care is extremely cost-effective (8–10). In fact, it has been estimated that the total cost of providing eyeglasses to those who need them is an order of magnitude less than the annual loss of global GDP due to URE (8).

Unfortunately, despite the clear impetus to correct refractive errors, the prevalence of URE remains disturbingly high. This is particularly true in low-resource settings, where 90% of those afflicted with visual impairments reside (11). The main goals of this review are to describe the major barriers that impede universal correction of refractive errors, existing methods to provide refractive care, and emerging technologies being developed to overcome these barriers. Other publications that take a more holistic view of the URE problem are available (4, 6, 12–14), so we have chosen to focus primarily on issues related to scientific and engineering challenges pertaining to diagnosis and treatment of refractive errors.

Uncorrected refractive errors (URE): refractive errors that could be corrected with eyeglasses but have not been

Visual impairment: VA worse than 6/18 in the better-seeing eye; this term encompasses low vision and blindness

Refractive errors: errors in the focusing of the relaxed eye that cause distant objects to be blurry

Blindness: VA worse than 6/120 in the better-seeing eye

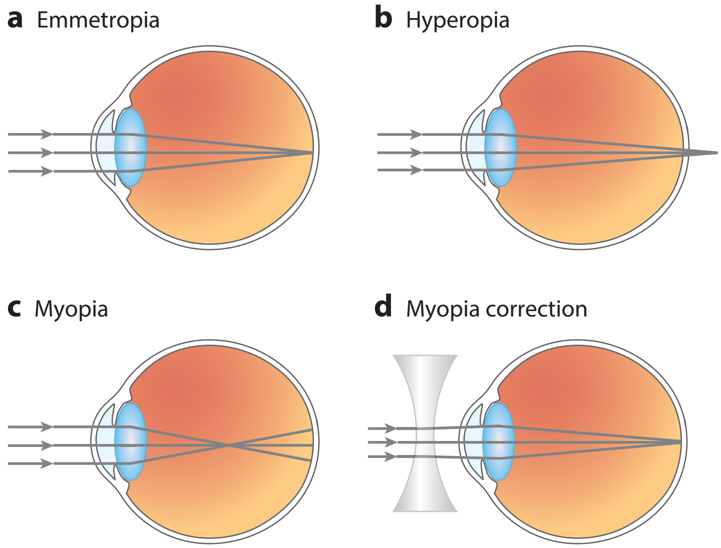


Figure 1

(*a*) An eye with no refractive errors focuses distant light to a small point on the retina (emmetropia). (*b*) In hyperopia, distant light is focused behind the retina. (*c*) In myopia, distant light is focused in front of the retina. (*d*) Prescription eyeglasses compensate for refractive errors to give sharp focus to a distant object on the retina. For example, a diverging lens is used to correct for myopia.

2. EPIDEMIOLOGY

2.1. Prevalence of Refractive Errors

The prevalence of refractive errors has been shown to vary across age group (15, 16), gender (15), region (17), and ethnicity (17, 18). These factors, added to the lack of standardization among existing studies (16, 19, 20), hamper an estimation of the global epidemiology of refractive errors. A major challenge in this estimation is that the refractive errors of the eye, quantified by diopters (D) of defocus or spherical equivalent (SE), lie somewhere on a continuum, and there are no clear thresholds for the amount of error that is clinically relevant—that is, thresholds that require prescription eyeglasses for correction. Instead, eyeglasses are prescribed by looking at the combinations of refractive errors that make up the prescription and by also taking into account the patient's age, preference, and, in some cases, occupation. For example, some studies define myopia as SE < -0.5 D, hyperopia as SE > 0.5 D, and astigmatism as cylindrical error >0.5 D (21–25). These definitions give rise to expansive estimates of the prevalence of refractive errors, as they include many subjects who would not conventionally be prescribed corrective eyeglasses. Herein, we report refractive error prevalences from studies that used a more clinically relevant threshold: myopia defined as SE < -1 D and hyperopia defined as SE > 3 D (17, 26) (see **Table 1**).

The prevalence estimations for astigmatism are not included in the table because the definition of clinically relevant astigmatism is even more variable than those of myopia and hyperopia, and most often, people with high astigmatism also have myopia or hyperopia. As small amounts of astigmatism are common (27), if a low threshold is chosen (cylinder of >0.5 D), prevalences ranging from 30% to greater than 50% can be found (23, 24, 28, 29). However, it is rare to have large astigmatism, so prevalence estimates reduce dramatically when higher thresholds are used. For example, a recent study involving more than 6,000 Iranian adults (30) reported prevalences of 49%, 24%, and 3% for astigmatism definitions of >0.5 D, >1 D, and >3 D, respectively.

Diopter (D): a unit measuring the optical power of a lens or eye by the inverse of its focal length (in meters)

Spherical equivalent (SE): the power of a purely spherical lens that corrects refractive errors such that the astigmatism is evenly split across different planes

Table 1 Prevalence of clinically relevant myopia and hyperopia

Region	Myopia (SE < −1 D)	Hyperopia (SE > 3 D)	Reference
United States	25%	10%	17
Australia	16%	6%	17
Western Europe	27%	12%	17
India	33%	16%[a]	26
China	17%	2%[b]	123

[a]Hyperopia prevalence in the Indian study is for a threshold of SE > 1 D.
[b]Calculated from 123.

Overall, approximately one in three Americans and Europeans have refractive errors that require correction (17). Myopia is the most prevalent and widely studied refractive error and has been linked to both genetic and environmental factors (16, 31). For example, a 2- to 10-fold increase in the prevalence of myopia has been observed among Asian children in urban compared with rural locations (16). The global urbanization over the past two decades may be partly responsible for the increasing prevalence of myopia (16, 32, 33). If current trends continue, it is expected that about one-third of the global population (≈2.5 billion people) will be affected by myopia within the next decade (34).

2.2. Prevalence of Presbyopia

Presbyopia is caused by an age-related decrease in the elasticity of the crystalline lens and capsule, resulting in an inability to accommodate and focus on near objects. This inability to change focus induces a defocus error for near vision only, so it is not conventionally considered a refractive error. However, presbyopia constitutes a large part of the world's need for eyeglasses. The correction for presbyopia requires reading eyeglasses, which correct for the defocus error at near vision as well as for the astigmatism present for all distances. Presbyopes without significant astigmatism commonly self-correct without an eye exam by purchasing off-the-shelf reading eyeglasses. The prevalence of presbyopia increases with age and is nearly universal in those over 55 years old. As of 2005, there were an estimated 1.04 billion people with presbyopia worldwide (35).

Visual acuity (VA): the sharpness of vision described by the ability to discern symbols at a standard distance (numerator, usually 6 m) equally well as someone with normal vision at another distance (denominator, in meters)

Refraction: the process of measuring refractive errors to determine an eyeglass prescription

Low vision: moderate to severe visual impairment (VA between 6/18 and 6/120 in the better-seeing eye)

2.3. Prevalence of Uncorrected Refractive Errors and Presbyopia

Several studies have estimated the magnitude of URE in specific regions and age groups (36–39). Defining URE as presenting with a visual acuity (VA) of less than 6/12 in the better eye that can be improved by at least two lines after refraction, prevalences of 10% (37), 15% (38), and 21% (36, 39) were found in Caucasian Australians, Latinos in the United States, and Singaporeans of Chinese or Malay ancestry, respectively. Unfortunately, estimates of the global population with URE are unavailable owing to differences in definitions and also the unreliability of extrapolating from population-specific data (20). Given this ambiguity, epidemiological studies have focused instead on measuring visual impairment, which encompasses both low vision and blindness but includes only a small subset of the population that suffers from URE. In 2004, the World Health Organization (WHO) estimated that 153 million people suffer from visual impairment due to uncorrected refractive errors (VI-URE) (2).

To provide an estimate of the global population with URE, we consider the prevalence data of URE from two well-regarded Australian studies—the Blue Mountains Eye Study (10%) (37) and the Visual Impairment Project (10%) (40)—and the 2004 WHO estimate of VI-URE in

Australia for the same age group (0.84%) (2). In these large data sets of similar populations, the prevalence of URE was approximately 10 times larger than that of VI-URE. Assuming that there is little variability in the ratio of URE to VI-URE among different demographics, we estimate that the global population with URE is 10 times larger than that with VI-URE. With this approach, we project that the global population with URE is 1–2 billion people.

For presbyopia, more comprehensive global prevalence studies exist. Holden and colleagues (35) estimated that of the 1.04 billion people with presbyopia in 2005, 517 million were disabled from poor near vision due to uncorrected presbyopia (DNV-UP). Local definitions of disability based on local standards of living were used in this study. A meta-analysis illustrating the geographic distribution of VI-URE and DNV-UP based on the 2004 WHO (2) and 2005 presbyopia data (35) is presented in **Figure 2**. China and India account for almost 50% of the worldwide VI-URE (1). For DNV-UP, 94% of the people with this disability (386 million people) live in developing countries (35).

2.4. Global Impact of Visual Impairment Due to Uncorrected Refractive Errors

The potential loss of global economic productivity for 2007 from VI-URE was estimated to be 269 billion international dollars (I$) (8). An implication of this number, which is more than 1,000

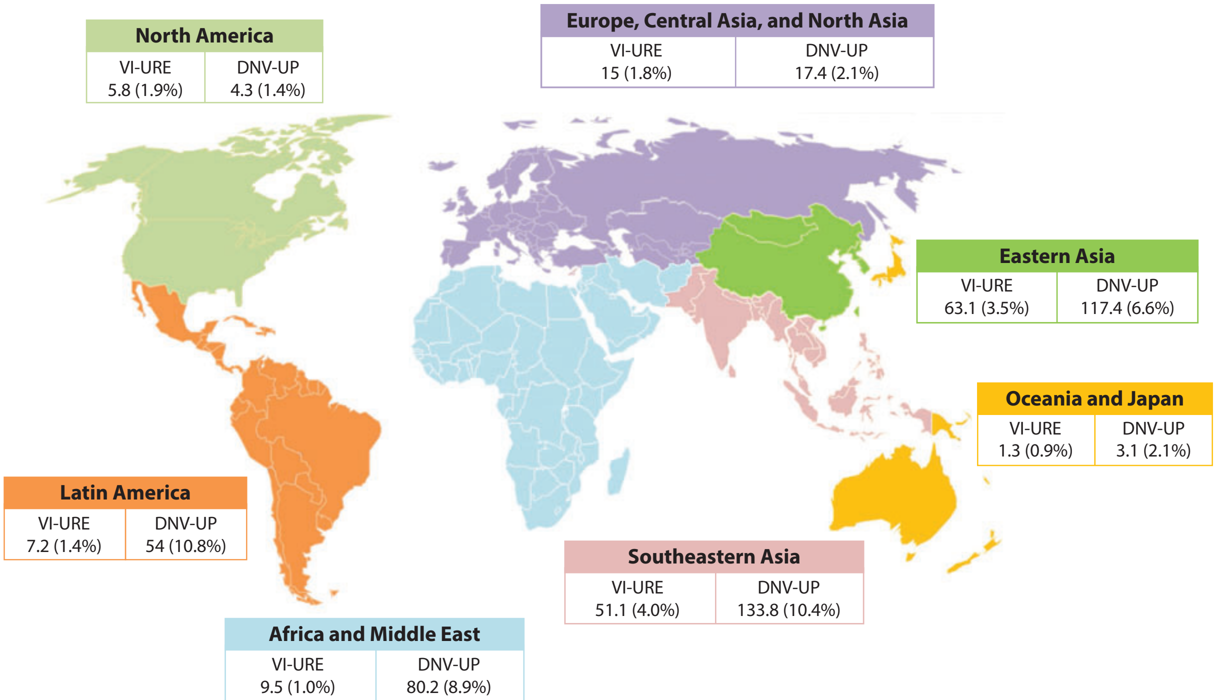


Figure 2

Geographic distribution of VI-URE and DNV-UP in millions (parentheticals indicate prevalence in each region). Data for VI-URE were obtained from the 2004 WHO report (2). DNV-UP data published by Holden and colleagues (35) are presented, and prevalence estimations were calculated using DNV-UP values and the 2004 WHO report population estimations (2). Regions with no available data (e.g., Greenland) were not included in the map. Abbreviations: DNV-UP, disabled from poor near vision due to uncorrected presbyopia; VI-URE, visual impairment due to uncorrected refractive errors.

times greater than the global number of cases of VI-URE, is that providing eyeglasses for less than I$1,000 to each person with VI-URE would result in a net economic gain (8). The impact of VI-URE has also been estimated using measures of health loss, such as disability-adjusted life years (DALYs) (41, 42) and years lived with disability (YLDs) (7). For instance, a WHO publication estimated that in 2004, 1.8% of all DALYs were caused by VI-URE, and the same report projected that by 2030, VI-URE would cause more DALYs than HIV/AIDS (42).

3. BARRIERS TO CORRECTING REFRACTIVE ERRORS

The lack of access to and restrictive economics of eye care are major drivers preventing correction of URE. However, further examination has revealed additional social and cultural barriers that are responsible for low levels of eye-care utilization and eyeglass adoption (14, 43). In two major surveys in southern India, participants listed economic (31% of responses), felt-need (23%), and access (16%) constraints as the major barriers (44, 45) to URE correction; as barriers to correcting presbyopia, participants listed felt need (46%), awareness (16%), and access (13%). Interestingly, somewhat different barriers—namely, personal (52%), economic (37%), and social (27%) constraints—were cited by subjects who noticed a decrease in VA yet did not seek care. Taken together, the difficulty in generalizing the barriers to URE correction using these terms is understandable (46). Therefore, to understand the technological characteristics required to address barriers to accessibility, we have chosen to categorize the barriers as follows: limitations of physical infrastructure and logistics that prevent the provision of care, socioeconomic factors that reduce the affordability of eye care, and inherent cultural constructs that oppose the utilization of eye-care services and eyeglasses.

Infrastructural and logistical barriers are among the most fundamental barriers to correcting URE. Within this grouping we include adequate physical infrastructure, well-trained and sufficient manpower, and availability of corrective eyeglasses. The shortage of human resources is particularly challenging to address because it takes years to build instructional facilities and train refractionists. Although the number of refractionists per country is not well known, it is clear that there is a severe shortage of refractionists, especially in developing countries (47–50). The shortage of ophthalmologists, by contrast, is well documented. Currently, low-income countries have an average of one ophthalmologist per 110,000 people, and many countries in Africa have less than one ophthalmologist per 1 million people (48). This is lower than the WHO Vision 2020 program's target of at least one ophthalmologist per 50,000 people in Asia by 2020 (49) and significantly lower than the one ophthalmologist per 13,000 people, on average, in high-income countries (48). The heterogeneous distribution of eye-care providers across populations also limits accessibility. Having to travel a distance of greater than 3 km significantly reduces the likelihood that a patient will visit an eye-care, or refractive, camp (51). Moreover, the quality of care available may dramatically differ in underserved areas. For instance, one study in rural China found that 50% of children were wearing eyeglasses whose prescriptions were off by 1 D or more (52). Recently, there have been increasing efforts to standardize the training and roles of eye-care personnel in low-resource settings (49, 53, 54). As ophthalmologists' training emphasizes eye disease and surgery, it is imperative to train optometrists and refracting opticians to fill most of the positions for refractive correction.

Socioeconomic barriers are diversely manifested and endemic in low-resource settings (43, 45, 51, 55). In places of high poverty such as regions of India and Timor-Leste, 96% of survey participants needing eyeglasses were willing to wear eyeglasses but were unwilling to pay US$1 for them (56). Nonetheless, the literature indicates that eyeglasses at US$3–5 (or about 2 days of wages) are generally affordable for many people of lower socioeconomic status (13, 45, 57, 58).

The cost-prohibitiveness barrier reflects not only the direct costs of the eye exam and eyeglasses but also the indirect costs of obtaining access to eye care, such as loss of daily wages and travel expenses (transportation, food, lodging) (13, 43–46, 55, 58). Similar costs arise in replacing lost, broken, or incorrect eyeglasses (59).

Having accessible and affordable eye care is not sufficient to eliminate URE. In many populations, a variety of cultural and personal barriers prevent utilization of eye-care services. Cultural definitions of good vision vary (45), and the ability to self-diagnose vision reduction (60) can depend on the need for VA for one's livelihood, highlighting extra barriers faced by illiterate laborers (43, 44, 55, 58, 61, 62). Also, a decrease in vision may not be considered a serious medical problem (57, 60), especially when a patient feels he or she can still see adequately, resulting in a lack of felt need (44, 45, 57, 60). In addition to fatalistic attitudes (51), gender and age also affect the perceived value of URE treatment (63, 64). Cosmetic stigma hinders eyeglass adoption and, for instance, has influenced some Pakistani women to discontinue use of eyeglasses and seek out contact lenses (57).

Infrastructural, socioeconomic, and cultural barriers to eye care also exist within developed countries and tend to disproportionally affect low-income communities (15, 65). In Australia, the ratio of population to optometrist or ophthalmologist in rural and remote areas was nearly one-half of that in major centers, which challenges the assumption of uniform infrastructural coverage in developed countries with universal health care (66, 67). Within the United States, the prevalence of vision loss among the Mexican American and African American communities was almost twice as high as that among Caucasians (68). This is partially attributable to socioeconomic barriers, such as low income, lower rates of health-care coverage, fewer visits to health services, and language (68–71). Other general barriers facing the population include access to transportation to the health services (especially for the elderly) (72), awareness of services (73), long waiting lines, trust and communication between the patient and health-care provider, and the overall cost of care.

4. EYE-CARE DEPLOYMENT

In low-resource settings, delivery of eye care is dependent upon infrastructure and manpower availability and can be organized into first point-of-contact by untrained villagers, mobile eye-care camps, basic care by community health workers with minimal training, and complete care by hospital systems.

Rural communities most often lack general medical facilities and have enlisted respected community members to fill the role of first point-of-contact for patients suffering eye-related ailments (74). Examples include traditional healers (75), community elders (76), birth attendants (49), and even shopkeepers (49, 54). In India, for instance, most remote villages have family-owned pharmacies that provide general medical advice, basic diagnoses, and medications. In such shops, a rudimentary eye consultation may be offered utilizing an eye chart to test for VA and a flashlight to detect cataracts. Eyeglasses are sold if available, or the patient may be referred to a nearby optometrist. These health providers typically have little or no formal training, and the government has recently tried to control and restrict their reach (77). However, these practitioners are often the only option for health care and are widely trusted by the communities they serve.

Several organizations, including Sight Savers America, ORBIS International, Volunteer Optometric Services to Humanity (VOSH) International, and Lion Clubs International, provide eye care in low-resource settings via mobile eye-care camps and screening programs. Though not a permanent solution, these outreach programs can be highly effective; for instance, in 2010–2011, Aravind Eye Care System set up more than 2,600 camps in Tamil Nadu, India, serving nearly one million patients and providing approximately 90,000 pairs of eyeglasses (**Figure 3*a***). Some

Figure 3

The accessibility of eye care in low-resource settings is being increased in several ways. (*a*) In refractive camps, well-trained personnel are temporarily sent to provide eye care in rural areas, where it is needed most. (*b*) Eye institutes in India are providing basic training and equipment to vision guardians to provide basic community vision screening. (*c*) Vision centers are being promoted by Vision 2020 as a more permanent solution for providing refractive eye care and referrals. The image in panel *a* is courtesy of Aravind Eye Care System; the images in panels *b* and *c* are courtesy of L V Prasad Eye Institute.

refractive camps customize and assemble the eyeglasses on site (13), whereas others record the prescription and ship the eyeglasses back to the community after they are manufactured elsewhere.

Eye-care institutes such as the L V Prasad Eye Institute, Aravind Eye Care System, and Sankara Nethralaya have recently transitioned away from reliance on transitory outreach programs, which reinforce patients' reactive attitudes, to community-based screening (54, 78, 79). The latter approach promotes trust owing to linguistic-cultural resonance and encourages a proactive attitude (79). The L V Prasad Eye Institute, for instance, recruits and trains vision guardians to perform screening and referral for their local communities (54). After a few days of training, vision guardians engage patients, promote the importance of eye care, perform a basic flashlight-based cataracts examination and an eye chart–based VA test, refer patients for further care if needed, deliver eyeglasses, and monitor patient compliance (**Figure 3*b***). A significant strength of this model is that screening is delivered directly at a subject's home by a trusted community member.

Two of the largest providers of eye care in the world, Aravind Eye Care System and the L V Prasad Eye Institute, have pioneered a sustainable pyramidal approach to eye care that encompasses both urban and rural centers and provides a full array of services, ranging from community screening to advanced surgeries (54, 78). At the primary level, where the bulk of URE are addressed, refractive care is provided by a vision technician. To increase retention, vision technicians are typically villagers with a secondary education living in the area in which they will serve (54). After being recruited and then trained for one to two years at the eye institute, they work in a vision center, where they perform screenings, refractions, and referrals (**Figure 3*c***). Vision centers serve approximately 50,000 people and require a start-up cost of US$8,000 (54, 80). At the secondary and tertiary levels, more comprehensive and sophisticated eye care is provided by highly trained personnel such as ophthalmologists (54). The successes of this eye-care pyramid have been promoted by the International Agency for the Prevention of Blindness (IAPB) and Vision 2020 infrastructural and human resource initiatives, which recommend the implementation of more than 20,000 vision centers each in India and China.

5. ESTABLISHED METHODS FOR MEASURING REFRACTIVE ERRORS

At its simplest, measuring refractive errors (a refraction) attempts to determine the eyeglass prescription that will provide the clearest possible image of a distant object on the layer of photoreceptors at the back of the eye of a patient. An eyeglass prescription consists of seven numbers that describe the characteristics that will produce sharp vision: the spherical power, cylindrical power, and cylindrical axis of both the left and right eyes as well as the interpupillary distance. In practice, however, a clinical refraction is not only an optical optimization problem; it must take into account the adaptations, preference, and comfort of the patient. Each patient may have a unique subjective interpretation of their aberrations and specific requirements for how their binocular vision should be corrected. Consequently, there is a certain art to prescribing eyeglasses (81, 82). Still, there are a number of technologies that aid and improve the refraction process. They can reduce, but have not yet eliminated, the expertise that is required to optimally assess refractive errors.

All approaches to refraction begin by shining light into the eye. From there, they can be divided into objective and subjective techniques. Objective techniques involve analyzing the light that is reflected from the retina of the eye, whereas subjective techniques rely on feedback from the patient during observation of different visual patterns. An efficient refraction conventionally uses both objective and subjective techniques in sequence. First, an objective measurement is made to quickly estimate the prescription. That estimate is then used as a starting point for a subjective measurement, which results in an eyeglass prescription that provides vision that is not only sharp but also comfortable for the patient. Ideally, the accuracy of the power parameters should be determined to the nearest 0.25 D, as that is the smallest increment at which conventional eyeglasses are manufactured.

5.1. Retinoscopy

Retinoscopy is the most common and arguably the most important technique for performing an objective refraction. A spot or streak of light is scanned across the center of the retina at the back of the eye, and the prescription is estimated by an examiner observing the motion of the retinal image reflection relative to the motion of the light entering the pupil. In a hyperopic eye, the image reflected from the retina is focused behind the examiner, so when the light is moved, the image of the light on the retinal reflection moves in the same direction as the light entering the pupil. Conversely, in a myopic eye, the image of the retinal reflection moves in the direction opposite that of the light that is scanned across the pupil. Converging or diverging lenses are then placed in front of the eye until the movement of the retinal image is stopped. This neutralization of movement provides a precise estimate of the refractive error. The optical power in both lateral and vertical directions can be measured independently, so the retinoscope can measure the astigmatic error as well as the spherical error.

The retinoscope is widely used in both low- and high-resource settings because of its robustness, low cost, portability, and speed. As of 2012, a battery-powered retinoscope can be purchased for US$250 in India. For the majority of patients, an experienced refractionist can estimate a prescription in a few minutes using a retinoscope. However, it takes several months of training to learn how to use and several years of practice to become proficient in the technique.

5.2. Autorefractors

Autorefractors are machines that automatically determine the optometric prescription needed to correct the primary optical errors of an eye. To measure the optical errors of the eye, they exploit one or often a combination of several optical principles, including parallax, split-image, Scheiner, reflex movement, best-focus, knife-edge, image size, ray deflection, and photorefraction approaches (83, 84). A comprehensive description of how these principles are used in a variety of autorefractors is presented in Rosenfield et al. (83). One of the most widely used forms of autorefractor is the eccentric autorefractor. In this design, a light beam is projected into the eye at a slight angle relative to a camera that is imaging the pupil. If the reflected light beam is seen in a pupil position slightly to the side of the pupil and on the opposite side of the entry beam, the eye is emmetropic. If the beam is farther to the opposite side, the eye is hyperopic, and if the beam is seen on the same side of the pupil as the entry beam, the eye is myopic. In principle, autorefractors are extremely simple and have proven to be effective. However, they require cameras and monitors for the examiner to properly center the pupil and are so large that they are table mounted. To achieve high signal-to-noise ratios without patient discomfort, most autorefractors use high-intensity near-infrared light that is reflected from the retina. This is problematic for two reasons. First, the planes that reflect the light do not necessarily coincide with the photoreceptor layer. Second, owing to chromatic aberrations, near-infrared light focuses at a different plane from those at which visible wavelengths focus (85). Both of these artifacts may contribute to differences between autorefractor measurements and subjective refraction and are typically compensated for by calibration.

The first autorefractors built in the 1970s were unable to accurately measure astigmatism, so they were not widely used by clinicians. Modern autorefractors are now more accurate and reliable and are frequently used in high-resource settings as an easy substitute for retinoscopy. Unlike retinoscopy, autorefraction can be performed by an optometrist's assistant with very little training. However, they are not commonly used in low-resource settings because they are neither portable nor inexpensive (in India in 2012, the cost of an autorefractor ranged from $7,000 to $15,000). Handheld autorefractors are also available, but they are not commonly used in low-resource settings because they are even more expensive than conventional autorefractors. Last, it is important to note that although the accuracy and reliability of autorefractors have increased dramatically over the past several decades, they are not commonly used as an alternative to subjective refraction because they have yet to predict the subjectively preferred prescription in a satisfactorily large percentage of patients (86–88).

5.3. Trial Lenses

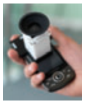
The simplest and earliest technique for performing refraction was to first have the patient look through a series of lenses of varying optical power (trial lenses) and then select the pair of lenses that makes distant objects look clearest. This process seems primitive, but it remains the gold standard and the nearly universally used end-point technique for refraction. However, there is considerable variability in the technique owing to both reliance on patient feedback and precision that is typically only ± 0.5 D (86, 89).

In most cases, refraction is performed after determining a starting estimate of the prescription by retinoscopy or autorefraction. Given this starting point, refraction with trial lenses typically takes an experienced examiner less than 10 minutes to perform. Years of practice allow an optometrist to master the sequence of steps to accurately and reproducibly refract with trial lenses.

Trial lenses can also be used for refraction without an initial estimate. This was the primary technique for refraction a century ago. The examiner provides spherical lenses in a preset sequence that is adjusted based on the patient's responses. If the patient reports being nearsighted or farsighted, the examiner starts with a diverging or converging lens, respectively. First the spherical error is minimized, and then a moderate-power cylindrical lens is introduced at different orientations to estimate astigmatism. If the patient reports improved vision at one of these orientations, the orientation and then the power of the cylinder are refined. The technique is straightforward in theory but takes considerable skill in practice. Refraction with trial lenses alone typically takes 20 minutes to complete.

Trial lenses are widely used for refraction in low-resource settings because of their low cost (US$250) and accurate results. Mechanical devices, called phoropters, combine many switchable

Table 2 Comparison of refraction devices for low-resource settings

Refraction device	Type	Current use	Training required	Refraction time (s)	Refractive errors measured	Price in low-resource setting
 Trial lenses	Subjective	Widespread	Advanced	500[a]	Spherical and cylindrical	\$250
 Retinoscope	Objective	Widespread	Advanced	100	Spherical and cylindrical	\$250
 Portable autorefractor	Objective	Select cases	Basic	10	Spherical and cylindrical	\$10,000
 NETRA	Subjective	Testing in low-resource setting	Basic	500	Full refraction data[b]	\$10[c]
 Adjustable lenses	Subjective	Testing in low-resource setting	Basic	100	Spherical	\$19[d]
 Low-cost autorefractor	Objective	Testing in low-resource setting	Basic	10	Full refraction data	TBD[e]

[a]Refraction time given an initial prescription estimate from an objective technique.
[b]Currently validated to accurately measure only spherical error (99).
[c]Price is for add-on only; a high-quality smartphone is also required.
[d]Current cost to manufacture is \$19 (93).
[e]Performance and price are to be determined; target price is <US\$1,000.

lenses into a single system that allows the examiner to quickly alternate lenses until the best is found. Phoropters are commonly used in developed countries, but because they cost an order of magnitude more than trial lenses, they are not commonly used in low-resource settings.

6. EMERGING METHODS FOR MEASURING REFRACTIVE ERRORS

Existing refraction technologies make some trade-offs in accuracy, speed, cost, portability, and ease of use. This section describes emerging technologies that attempt to ameliorate the accessibility of refractive care in low-resource settings by circumventing some of these trade-offs (**Table 2**).

6.1. Self-Refraction by Adjustable Lenses

One obvious approach to subjective refraction is to have the patient try various lenses themselves, maximizing perceived image sharpness. Similar to refraction with trial lenses alone, this process is time-consuming and challenging, but it can be successful if a systematic routine is used. If the patient is assumed to have minimal astigmatism, the problem is more manageable. In such cases, only one degree of freedom needs to be changed (spherical power), and it is possible for efficient subjective self-refraction by iteration. In fact, this is the common practice for correcting for presbyopia in people with low astigmatism—the subject typically tries a variety of premade eyeglasses (reading glasses), which have purely spherical correction, and selects the pair that is most comfortable at the distance from which the subject most commonly reads.

There are several techniques to estimate the spherical component of the prescription. People can use a set of lenses with varying spherical power and select the one that gives the sharpest image for each eye (90). Another approach is to use a focometer—a monocular device with continuously adjustable spherical power. The subject can adjust the focometer to maximize sharpness, and read out the spherical power from a ruler on the device (91). Last, eyeglasses with adjustable-power lenses can be used. This approach is particularly intriguing because not only are adjustable eyeglasses a tool that enables self-refraction, but they also provide the treatment: At the end of the test, the adjusted eyeglasses can be fixed at the chosen power and then given to the patient as corrective eyeglasses.

The Centre for Vision in the Developing World has been implementing low-cost, adjustable-lens eyeglasses that use liquid-filled lenses (92). The center has tested its solution in the United States, China (93), Africa, and Southeast Asia (92) and has distributed thousands of pairs of eyeglasses. Still, there are several challenges to overcome: (*a*) Astigmatism is not corrected; (*b*) a slightly larger curvature must be created to achieve significant spherical correction; (*c*) higher-order aberrations are induced, especially when the wearer looks off-axis; (*d*) the current manufacturing cost of adjustable eyeglasses (US$19) is several times greater than the purchase price of the cheapest conventional prescription eyeglasses (93); and (*e*) current versions of adjustable eyeglasses suffer from poor aesthetic design. Some of these challenges are currently being addressed—for example, a new design with a larger field of view and improved appearance is currently being developed. The simplicity of the approach, along with the ability to provide both refraction and immediately wearable eyeglasses, may eventually prove to be useful in increasing accessible refractive care at a large scale.

Another approach to implement adjustable lenses uses a set of Alvarez lenses, the spherical power of which can be tuned by sliding a pair of lenses relative to one another (see **Figure 4*a***) (94, 95). Eyeglasses using Alvarez lenses are now being developed by several organizations (see **http:www.focus-on-vision.org**, **http://www.eyejusters.com**, and **http://www.adlens.com**). Alhough Alvarez lenses offer some design advantages over liquid lenses, such as the possibility to create more stylish, noncircular lenses, there is concern over their robustness to water and sand owing to the gap between the sliding lenses, and there is significant off-axis distortion. Recently, a self-refractor using a set of adjustable lenses that can control both spherical and cylindrical correction has been proposed (96). Although this approach is promising, in addition to facing

Figure 4

Emerging methods for measuring refractive errors. (*a*) For myopia and hyperopia with minimal astigmatism, adjustable lenses provide not only a tool for self-refraction but also the customized eyeglasses at the end of the test. (*b*) EyeNetra seeks to increase accessibility to eye care by developing an affordable cellphone add-on that enables prescriptions to be measured without an expert. (*c*) Our group is developing a low-cost autorefractor that utilizes wavefront aberrometry to automatically measure a prescription in the hopes that it will increase the eye-care provider's efficiency and, perhaps one day, supplant subjective refraction in low-resource settings. The images in panel *a* are courtesy of Eyejusters. The images in panel *b* are courtesy of the MIT Media Lab (*left*) and EyeNetra (*right*).


a
b
c

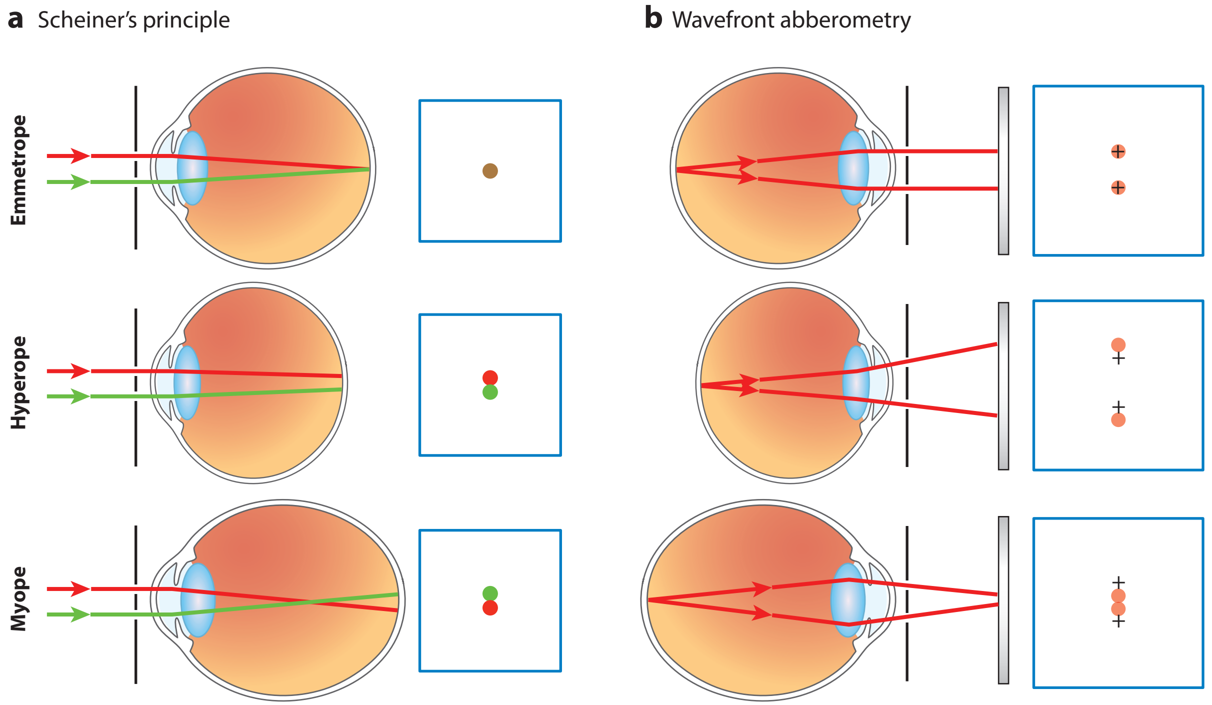


Figure 5

An eyeglass prescription can be measured by structuring the light entering the eye (Scheiner's principle) or structuring the light exiting the eye (wavefront aberrometry). (*a*) Collimated rays of light will form an image of one point on the retina of an eye without refractive errors (emmetrope) and will form an image of multiple spots if the eye has refractive errors. (*b*) If a point source is illuminated on the retina, the light emitted from the eye can be analyzed with a wavefront aberrometer to measure the refractive errors.

some of the same barriers conventional adjustable glasses face, there is another challenging obstacle: A straightforward procedure must be developed for instructing the patient to iteratively adjust the three degrees of freedom to converge on the correct prescription.

6.2. Subjective Refraction with Scheiner's Principle

One of the earliest devices used to assess refractive errors is the Scheiner disk, which was introduced in 1619 (84). A double pupil is placed in front of the eye and illuminated. If the subject sees one spot, the eye is emmetropic along the axis of the two pupils (**Figure 5*a***, *top*). If two spots are seen, the eye is emmetropic. Astigmatism can be evaluated by rotating the axis of the double pupil. In 1989, this technique was improved to provide a more quantitative estimate of the prescription and accommodative control (97). The Scheiner principle is used by some autorefractors (83), but the Scheiner disk is not accurate enough to be practical for refraction.

More recently, a device called NETRA, a programmable lenticular display to subjectively assess refractive errors, has been developed (98). The user looks through the device (see **Figure 4*b***) and, owing to Scheiner's principle (**Figure 5*a***), sees multiple lines separated by a distance that depends on his or her refractive errors. As the user provides feedback describing the gap, the lines on the display are moved and the NETRA algorithm records the conditions when the user sees the lines completely overlapping. Based on these conditions, the NETRA calculates a prescription. A major goal of this project is to increase accessibility to refraction in low-resource settings. NETRA offers two primary advantages: (*a*) If the user has access to a smartphone with a high-quality screen, the NETRA device can be made by attaching a very low-cost (∼US$10) accessory component, and (*b*) someone with little training can potentially use NETRA to perform refraction. However, there are many challenges that NETRA must overcome to become a useful tool. First, its accuracy must be improved, especially in measuring astigmatism (99). As a subjective technique, NETRA performs relatively slow refraction, and the accuracy of its prescription depends on quality feedback from the subject. Also, unlike traditional subjective techniques such as trial lenses, NETRA places no physical lens in front of the eye; as a result, the subject cannot evaluate the comfort or verify the accuracy of the measured prescription. Instrument-induced myopia may also be an issue (100, 101). User instructions for obtaining a refractive prescription with NETRA can be complicated, which may limit the device's usability for certain subjects (99).

6.3. Photorefraction

Photorefraction, or now videorefraction, is a technique that analyzes photographs or videos of the eye to estimate the prescription (102, 103). Typically, a set of LEDs is used as a light source to illuminate a spot on the fundus of the eye. In orthogonal and isotropic photorefraction, the size and shape of the spot imaged by the camera are then used to determine the prescription. Alternatively, in eccentric photo- or videorefraction (also called photoretinoscopy), the position of the spot image during dynamic or structured illumination is analyzed to determine the prescription (83, 104). Although these techniques are, in principle, extremely simple and potentially low-cost, they are not yet sufficiently accurate to prescribe eyeglasses, and the range of refractive errors that can be measured is more limited than that with conventional autorefractors (83). Consequently, photorefraction is not currently used for dispensing prescriptions but is instead used as a screening tool for anisometropia and strabismus in children (105–108). However, if the accuracy and range of these techniques can be improved, photorefraction could be an appealing technique for refraction in low-resource settings because of its speed, low cost, and ease of use.

6.4. Wavefront Aberrometry

Above, we have described refractive errors assuming that they result entirely from defocus errors, which are lower-order aberrations. But, the complex ocular lens system also introduces higher-order aberrations, such as coma, trefoil, and spherical errors, that account for an additional 0.3 D of defocus in the average eye (109). Wavefront aberrometry is a technique that can measure both the lower- and higher-order aberrations of an eye. This technique works by illuminating a point on the fundus of the eye, then measuring with a wavefront sensor the light field that is remitted by the eye. A conventional wavefront sensor consists of a pinhole array or lenslet array that constrains the remitted light to a pattern of spots that are detected with a 2D detector array, such as a charge-coupled device (CCD). The position of each spot on the image sensor is directly related to the tilt of the portion of the wavefront entering each lenslet (**Figure 5*b***). Thus the phase of the wavefront can be calculated from the spot positions, which then can be related to the aberrations of the eye. The more spots that are measured over the pupil, the greater the number of aberrations that can be measured. A comprehensive review of the principles and design considerations involved in wavefront aberrometry is presented in Dai (110).

Conventional wavefront aberrometers provide excellent estimates of eyeglass prescriptions but are so complex and expensive that their use is typically confined to guidance of refractive surgery. With the aim of increasing the efficiency of optometrists, our group is developing a portable, easy-to-use wavefront aberrometer that may work as an inexpensive autorefractor (see **Figure 4*c***). Furthermore, if the entire aberration profile of the eye can be reliably measured, there is evidence that the prescription determined by a wavefront aberrometer can closely match that produced by subjective refraction (111–113).

7. REFRACTIVE ERROR CORRECTION

Once the prescription has been determined, there are two main approaches to correcting refractive errors—by using refractive devices, such as eyeglasses and contact lenses, or by surgery. Of these options, by far the more cost-effective method is the use of eyeglasses. As such, eyeglasses are the de facto choice for correcting refractive errors in low-resource settings, as recommended by the IAPB (12).

The most challenging eyeglasses component to produce is the lens, which is typically made of glass or plastic. Once both lenses have been crafted, they can be inserted straightforwardly into a frame to complete the eyeglasses. Glass lenses are more scratch resistant, less expensive, and typically thinner than plastic lenses. However, glass lenses also tend to be heavier and more prone to breakage. Lenses are prepared from lens blanks, which have to be edged and beveled at the optical shop to fit the customer and the chosen frame. Glass lenses are easier to prepare and can be edged with simple hand tools, enabling glass lens eyeglasses to be produced on-site in small vision centers and mobile refractive camps. In these settings, plastic lens prescriptions have to be sent to the city to be filled, delaying the delivery of eyeglasses and reducing compliance.

8. CHALLENGES AND FUTURE PROPOSALS

There is a clear need to reduce the infrastructural, socioeconomic, and cultural barriers that restrict the accessibility of eye care. Many of these barriers are currently (and appropriately) being tackled by policy and institutional changes (6, 13, 54; see also **http://aravind.org/**). Yet there is still much that can be done through technology development to improve the situation. A major challenge is that there is an acute shortage of trained personnel who are able to perform refractions. One way to improve this problem is to increase the efficiency of existing refractionists, with, for example, a more affordable, portable, and reliable autorefractor. The problem of disparate optometrist-to-population ratios in rural and urban environments (66) may be circumvented by introducing equipment that can be operated or analyzed remotely (114). Another impactful goal to pursue is to create devices that require less training to learn how to operate or even, as is the goal with NETRA and adjustable lenses, devices that can be used unsupervised—that is, ones that are operated by the patients themselves.

Trial lenses are an imperfect gold standard for refraction. The holy grail in refractive eye care is perhaps a device that enables objective refraction that prescribes eyeglasses that are better tolerated than those prescribed by subjective refraction. This would be ideal because, as objective techniques do not rely on patient feedback, they can, in principle, be faster, more precise, and easier to use than trial lenses. Aberrometry-based objective refraction may eventually fulfill this requirement (113, 115), as it shows potential to provide reliable prescriptions that closely match those from the subjective gold standard, in a fraction of the time and with minimal operator training.

Something to be wary of in developing technologies that circumvent eye-care providers is that a comprehensive eye exam includes more than just refraction. The optometrist also screens for important diseases such as glaucoma and diabetic retinopathy. Providing refraction without screening for these diseases could be damaging for those that need more serious health care. With this in mind, it is also important to create hybrid devices that are capable of screening for several diseases simultaneously, such as the 3nethra device from Forus Health.

Although it will likely never be practical in the lowest-resource settings, it is also worth considering the role of laser eye surgery in reducing URE. Unlike correcting refractive errors through eyeglasses, surgery avoids compliance issues. This is a nontrivial advantage—even in populations to which free eyeglasses were provided, low compliance has led to persistent URE (116, 117). However, there are obvious downsides to refractive surgery, particularly in low-resource settings—namely, scarcity of ophthalmologists and sterile operating conditions, increased risk of complications and infection, unsuitability for patients below age 21, and, most importantly, the high cost of surgery. However, this last point is perhaps more nuanced than one might first imagine because, unlike the use of eyeglasses or contact lenses, refractive surgery is a procedure that is effective for many years. In high-resource settings, it has been suggested that over the course of 10–30 years, refractive surgery is more costly than eyeglasses but less costly than contact lenses (118). This does not take into account the quality of life improvement associated with refractive surgery (119–121). With future improvements in the affordability, reliability, and ease of use of surgical technologies, there may be some role for refractive surgery to play in reducing the prevalence of URE.

Last, it is important to mention that some of the most impactful innovations for improving eye care may come not from the engineering of novel devices alone but instead from synergistic combination of novel technologies, business models, and policies. Creating new ways to profitably meet the eye-care needs of those in low-resource settings may be the most sustainable and scalable approach to improve poor vision (122). We are well into the digital age, yet technologies and models for basic refractive care in developing countries have hardly evolved over the past century. Furthermore, with the global trends of aging populations, growing economies, and an increasingly high-tech workplace, the demand, importance, and relevance of eye care will only increase. URE are far from a solved problem. Indeed, there are still plenty of opportunities for innovative research and engineering to help eradicate, or at least alleviate, this global challenge.

SUMMARY POINTS

1. URE are a major source of global disability despite having a simple, effective, and low-cost solution—namely, a pair of prescription eyeglasses.
2. Although there are no reliable data describing the global prevalence of URE, those disabled with VI-URE number in the hundreds of millions and are concentrated in the developing world. The population with URE is likely more than one billion people.
3. The three major barriers to providing refractive eye care in low-resource settings are (*a*) awareness of and/or desire to correct poor vision, (*b*) cost of the diagnosis and treatment, and (*c*) access to professional eye care.
4. The most common approach to refraction in low-resource settings utilizes a retinoscope and trial lens set to determine the prescription. These technologies restrict accessibility to low-cost eye care because they are slow and their proficient use requires years of professional training.
5. Several emerging technologies—including adjustable lenses (Adspecs, Adlens, Eyejusters, FocusSpec), a self-administered subjective test (EyeNetra), and a low-cost, easy-to-use autorefractor (our work)—aim to improve refraction in low-resource settings.

6. To meaningfully reduce URE in low-resource settings, we need new technologies that are simultaneously accurate, easy to use, low-cost, fast, and robust. To maximize the impact of these new technologies, they may ultimately need to be paired with innovative business models and deployment strategies.

DISCLOSURE STATEMENT

N.J.D., S.R.D., E.L., S.M., and D.L. are inventors on provisional applications for patents that are relevant to some of the technologies presented in this review. They may receive royalties if these patents are licensed. Additionally, N.J.D., S.R.D., E.L., and D.L. are founders of PlenOptika, Inc.—a company that is commercializing an autorefractor similar to that presented in **Figure 4*c***.

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