Environmental Light and the Preterm Infant

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The lighting environment of the preterm baby is quite unlike that experienced at any other time of life. Physical and physiological factors control how much light reaches the retina of the preterm baby. With respect to the former, although many neonatal intensive care units are brightly and continuously lit, there is a trend to employ lower levels of illumination and to introduce cycling regimens. Physiological determinants of the retinal light dose include: eyelid opening and transmission, pupil diameter and the transmission characteristics of the ocular media. Early exposure to light does not significantly hasten or retard normal visual development, and it is not a factor in the development of retinopathy of prematurity. However, ambient neonatal intensive care unit illumination may be implicated in some of the more subtle visual pathway sequelae that cannot be attributed to other major complications of preterm birth including altered visual functions and arrested eye growth.

The infant born prematurely is placed in an environment quite unlike that experienced at any other time of life. This article considers environmental light and the preterm baby and how it may affect the infant and the visual system. This account will be divided into 4 main sections: (1) The amount of light received by the infant, (2) The amount of light received by the neonatal eye, (3) The effect of light on the baby, and (4) How light might affect the developing visual system.

Light is defined as that portion of the electromagnetic spectrum (EMS) responsible for visual sensation and extends from approximately 400 to 760 nm. Optical radiation includes, in addition to light, ultraviolet (UV) radiation (100 to 400 nm) and infrared (IR) radiation (760 nm to 1 mm). UV and IR though functionally irrelevant for vision in humans are nonetheless potentially hazardous to component structures and tissues of the visual system.

Optical radiation can be measured in either radiometric or photometric units. Radiometry makes reference to absolute physical quantities whilst photometry weights measured physical quantities by the sensitivity of the visual system. Radiance and luminance are the respective radiometric and photometric terms for the amount of energy emitted from a source and irradiance and illuminance are the terms relating to light falling on a surface (eg, a baby's face or cot). Irradiance is measured in units of watts/m^{-2} and illuminance, the photometric analogue of irradiance in lux (lumen/m^{-2}) or foot candles (1 fc = 10.76 lux).

Light Dose—To the Infant

The neonatal light dose is largely governed by environmental or physical factors including the intensity and spectral characteristics of the light, and the duration of exposure.

Preterm babies are cared for in neonatal intensive care units (NICUs) which are typically illuminated 24 hours a day by a mixture which consists variably of daylight and fluorescent tubes. Most studies of NICU lighting describe only illuminance,[1-11] and so do not adequately quantify the amount of the shorter wavelengths in this environment.

Reported lighting levels range from 400 to 1,000 lux during the day to 50 to 100 lux at night, if a cyclic lighting regimen has been introduced.[4,11] Values in excess of 10^4 lux have been reported for nurseries in the US where daylight supplements the overhead lighting.[1] Lighting levels vary between and within NICUs and are influenced by seasonal factors.[6,7] A United Kingdom study about a decade ago monitored light over the 24-hour period and except for 2 low dependency areas, all NICUs were brightly and continuously illuminated.[4] During the day, the mean illuminance was 470 lux

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(range, 236 to 905 lux), while at night, when the lighting was provided solely by fluorescent sources the mean illuminance was 348 lux (range, 192 to 690 lux). In 2 NICUs a policy of reducing the level of artificial light in the low dependency areas at night kept the minimum illuminance at 50 lux.

The American Association of Pediatrics for Guidelines for Perinatal Care in 1992[12] recommended illumination maxima of 60 fc (650 lux) for observation, and 100 fc (1080 lux) for procedures.[13] The Committee to Establish Recommended Standards for Newborn ICU Design, 1993,[13] pointed out the benefits of diurnal variation and recommended that if possible light should be directed away from the eyes of the infant.

The spectral characteristics of NICU lighting[2,10] show that fluorescent tubes can emit over 40% of their total energy in wavelength bands outside the normal photometric range so they significantly underestimate the amount of light reaching the infant especially at short-wavelengths. Both the irradiance and illuminance surveys showed significant and consistent differences between the high and low dependency regions. In one survey[10] mean irradiance in 2 NICUs for high and low dependency (HD and LD) areas was: 149 $\mu W/cm^2$ (HD) and 36 $\mu W/cm^2$ (LD) for 400 to 500 nm, 297 $\mu W/cm^2$ (HD) and 117 $\mu W/cm^2$ (LD) for 500 to 650 nm. The spectral characteristics of the NICU are weighted toward the shorter wavelengths, in the 'blue light' hazard range.

Many factors influence ambient lighting levels, and these include location within the NICU, seasonal and climatic variations, and infant-related factors.[14] The latter include: head position (the eye closer to the mattress is more likely to be closed), shielding of the lower eye, by clothing, an arm, or the mattress. The lower eye or eyelids (eye closer to the mattress) receives a mean of 25% (range, 0% to 78%) of environment light, whereas for the upper eye or eyelids (eye away from the mattress) this mean value is 86% (range, 57% to 100%).[6,14]

Infants are also exposed to light sources both as part of their treatment and during examinations. Premature infants are often exposed to phototherapy (2,400 to 3,000 lux between 425 to 470 nm and a small amount of UV 330 to 400 nm, depending on the phototherapy type[15]) for the treatment of neonatal jaundice.[16] During phototherapy, which may last for several days, eyes are shielded from the phototherapy light source by 'patches.' Eyeshields securely in place will attenuate more than 90% of the light emitted by a phototherapy source[17-19] and reduce the potential risks of photokeratitis due to UV exposure and retinal injury mediated through the blue-light photochemical mechanism. However, eyeshields were shown to slip away from the eyes in over half of all observations in one study.[20]

Other sources of light include events surrounding ophthalmoscopic examinations screening for retinopathy of prematurity (ROP). This requires pupillary dilatation, the effect of which lasts at least 18 hours (Robinson, Lawson, and Fielder, unpublished data, 1992). The potential light hazard posed by the indirect ophthalmoscope[21] per se is probably small compared to the effect of the pupillary dilatation.

Thus the fetus is transported from the uterus with its low level of illumination (maternal abdominal wall light transmission $\sim$ 2%[22]), into an environment quite different from that experienced at any other time of life. NICU illumination levels have risen 5- to 10-fold over the past 3 decades,[1,2,4,23] however there is recent evidence that NICU lighting levels are falling again. Thus the study of Bullough et al[24] revealed daytime and nighttime illuminance levels of 184 and 34 lux respectively, much lower than those reported previously. As yet this tendency is not universal as the mean lighting levels reported in the LIGHT-ROP Study were 399 and 447 lux for babies with and without goggles respectively.[25] The trend towards lower NICU illumination was probably initiated by the study of Glass et al in 1985[26] that reported an association between lighting levels and retinopathy of prematurity. Another factor encouraging the use of low lighting levels is the introduction of Newborn Individualised Development Care and Assessment Programs (NIDCAP). NIDCAP aims to optimise infants' development by reducing stress, augmenting self-regulatory efforts, and providing a parental envelope which facilitates the infant's development.

The recent trend toward lower and cycled NICU lighting levels is reflected in the 1999 Recommended Standards for Newborn ICU Design, which recommend ambient lighting levels of 10 to 20 fc,[27] and that sources should be filtered for ultraviolet radiation. The authors of this document recognize, however, that the supporting evidence for these recommendations is based largely on expert opinion rather than objective data.

Light Dose—To the Neonatal Eye

Although most of the factors determining the amount of light reaching the infant are environmental or physical, in contrast, those that influence how much of this ambient light reaches the interior of the neonatal eye, are biological. These determinants, which will now be considered, include eyelid opening and transmission, pupil diameter, and the transmission characteristics of the ocular media.

Frequency and pattern of eyelid opening have been examined,[20,28] and the one study to monitor this over the 24 hour period, revealed a mean eyelid closure of 74%.[20] However, eyelid opening is a function of postmenstrual age; babies of less than 26 weeks PMA had their eyes shut for 55% of observations compared with 93% at 28 weeks PMA and 60% at 34 weeks PMA. This temporal sequence is not influenced by preterm birth, although those babies subjected to a day or night regimen opened their eyes significantly more than those exposed to continuous illumination.[20] Trend analysis confirmed that eyelid closure reached a peak at 28 weeks PMA.

The amount of light reaching the interior of the eye is influenced by the transmission characteristics of the eyelids when they are closed. For the adult,[29,30] and preterm infant,[30] the peak transmission, in vivo, is at the red end of the spectrum (700 nm) and at this wavelength 14.5% light in the adult and 21.4% in the preterm infant are transmitted. At both ages less than 3% light below 580 nm passed through the eyelid.

The passage of light through the ocular media is determined by the absorption, scatter and reflection by the ocular tissues. The ability of radiant energy to damage the ocular tissues is largely determined by the spectral transmittance and/or absorbance properties of each tissue.[31-36] Both are wavelength dependent, and thus influence the spectral composition of light absorbed by the retinal photopigments. The spectral transmission properties of the ocular tissues taken as a whole was determined by Ludwigh and McCarthy[34] from adult eyes and later 'corrected' for age. The cornea transmits radiation from 295 nm (UV) to 2,500 nm (IR). Transmittance increases rapidly from 300 nm reaching about 70% at 380 nm and over 90% across the 500 to 1,300 nm range. The crystalline lens transmits radiation from 350 to 1,900 nm. Transmission of the lens decreases with age especially at the short wavelengths—the lens thus acting as a shortwave filter notionally providing protection for the aging retina. Thus, the cornea, aqueous, and lens normally filter out most radiation below 400 nm. The ocular media of neonates are highly transmissive, compared to the adult, especially in the blue and UV regions of the spectrum, and the lens at this time transmits more than 90% of light less than 420 nm. Finally, light does not enter the eye exclusively through the pupil, as the sclera and choroid also transmit about 14% of light,[33] again predominantly at the red end of the spectrum.

The final physiological factor that modulates light entry to the retina is pupil size.[37] The iris is not reactive to light until the pupillary light reflex develops between 30 and 34 weeks PMA.[38-40] Before the onset of this response the mean horizontal pupillary diameter is 3.5 mm compared with 3.0 mm after the reflex development.[40]

Based on the above data an estimate of the retinal irradiance received by a preterm neonate can be derived and has been shown to be inversely related to gestational age (GA) or PMA: $\sim$530 μW/cm^2 at 24 weeks PMA reducing to $\sim$240 μW/cm^2 at 32 weeks PMA.[5,6,10,11]

Effect of Light on the Infant

One aim of modern neonatology is to create an environment which mimics that experienced in utero as closely as possible.[41] However, the NICU environment is not optimal for preterm neonates[8,42-46] as it differs significantly from that experienced by the fetus, at least with respect to noise, light, temperature, and handling.[8,46] The amount of handling ranges from about 10 times to over 200 times a day.[20,47] Of course meeting the requirements of modern neonatal care is the critical issue, but it could be argued that this has dominated the thoughts of carers so that the neonatal environment has not received the attention it merits. Attention is now being so directed, and supported by NIDCAP. However, the neonatal environment is so complex that it is frequently difficult, if not impossible, to disentangle the possible influence on the baby of one component from another. Thus, after lowering illumination, it has been observed incidentally that babies are handled less and noise levels also fall.[48] In addition, Lawson et al stated that there are frequently major differences between NICUs that precludes the concept of a 'typical' NICU.[44] With these caveats we will attempt to address the effects of environmental light on the neonate.

Changes in environmental illumination induce several transient or short term effects. Lowering the level illumination produces an immediate and transient eyelid opening followed by significantly longer periods of opening when dimmed illumination is maintained.[20,28] Reduced illumination has been found to increase the infant's stability, respiratory stability, and reduce heart rate, blood pressure, respiration rate, and motor activity.[48-50] Chest shielding has been reported to reduce and delay the onset of patent ductus arteriosus making subsequent management easier.[51] Constant lighting reverses the normal diurnal variation in blood amino acid concentrations.[52] The consensus view is that under conditions of reduced illumination, infants are generally more stable and energy conserving. Shogan and Schumann[53] observed that increasing illumination from 54 lux to 1,076 lux reduced oxygen saturation in the smaller preterm neonate, although reversing the condition had no significant effect. These authors also noted that noise precipitated oxygen desaturation.

The development of day-night, sleep-wakefulness patterns in preterm infants is discussed elsewhere in this issue of *Seminars of Perinatology*. Abnormal sleep patterns are well known in preterm infants[26,46,54] and Mann et al,[54] observed that exposure to a day and night cycling regimen in the NICU is beneficial with regard to feeding, weight gain and sleeping behavior compared to age-matched controls. This effect however was not immediate but only observed between the time of discharge and 3 months. They also made the important comment that these effects might be mediated by an indirect, rather than a direct effect of physical properties of light, akin to the comments already made[48] that lowering illumination also affected staff behavior so that there was less activity in the nursery and the ambience became generally more quiet. These secondary effects of lowering illumination might not be observed therefore if the level of environmental light is reduced by the use of goggles worn by the infants without affecting the caregivers environment. This paradigm was employed by the randomized control LIGHT-ROP study (see later) in which babies were allocated to wear or not to wear light reducing goggles.[25] There was no difference between goggled and control infants in weight gain, intracranial hemorrhage, duration of supplemental oxygen therapy, duration of mechanical ventilation or duration of hospitalization.[55] This supports therefore the hypothesis that the effect of lowering illumination on the infant could be mediated secondarily through the caregiver rather than directly through the infant.

Future studies should reconsider these observations in the light of comments by Shimada et al[56] who stated that until the retinohypothalamic pathway becomes functionally active (about 40 weeks PCA) light-dark cycling was not important for the development of entrained sleep-wakefulness patterns. Pursuing this issue further, Sell et al[57] have observed that nursing/medical interventions induce behavioral disorganization, its magnitude being PMA-related. These studies all signify the complexity of the neonatal environment with the interaction of many factors, and which may be considered variously as inadequate, adequate, or excessive, and having consequences for future physical, cognitive, and social development.[44] Of course this makes our avowed aim of identifying the specific effects of light exposure on the neonate all the more challenging.

Effect of Light on the Developing Visual System

Normal Development

Premature birth removes the fetus from the protective uterine milieu, which is ideally suited to promote growth, and exposes its immature tissues to an environment that we now know to be particularly harsh and unlike that experienced at any other time of life. The effect of light on the human developing visual system is unknown, and there are many mechanisms by which retinal metabolism may be altered, such as free radical generation, altered oxygen consumption and capillary endothelial growth, photoreceptor regeneration.[5,10,58-65]

Being born early with its attendant early exposure to light may accelerate, retard, or have no effect on visual development. So far the evidence indicates that the visual system before term is rather resistant to any alteration of illumination. Thus, light reduction by goggling (reducing 97% light and 100% ultraviolet radiation) does not affect the electroretinogram of preterm infants.[66] Similarly a small group of infants that were totally occluded from 29 to 32 weeks PMA exhibited no difference compared to unoccluded subjects in their pattern evoked potentials at 41 and 51 weeks PMA and at 3 years of age.[67] In general, visual development is governed mainly by innate processes and proceeds largely unimpeded by preterm birth,[6] although a minimal degree of hastening cannot be entirely ruled out.[6]

Retinal Light Damage

The retina is susceptible to damage by light although unsurprisingly the dose-effect relationship for light damage and the human developing visual system is unknown. Retinal photochemical damage is determined by: the physical nature of the exposure (wavelength, intensity and duration), age (greater resistance to light damage with increasing age) and the precondition of retina, such as its state of dark-adaptation and oxygenation. This is not the place for a detailed discussion on light damage, but suffice it to say that retinal photochemical damage occurs with both long exposure to low light levels and to shorter duration exposures to high intensity stimuli.[68,69]

The human infant has several natural light-protective mechanisms, such as gaze aversion, eyelid closure and blinking, and shielding[14] and these are often increasingly augmented by the carers. However, the preterm neonate is placed in lighting environments of sufficient intensity to cause damage in animal models,[5,6,10,11] although as yet we do not know whether the visual system is actually damaged by light exposure in the preterm period.

Retinopathy of Prematurity

Early exposure to light was suggested as a causative factor in the first descriptions of this ROP by Terry.[70,71] Studies by Hepner et al in 1949[72] and Locke and Reese in 1952[73] did not provide supportive evidence and interest in this topic waned. This finding is not unsurprising as during this period before 1953, the high amounts of supplemental oxygen being administered could well have swamped any effect of light. Riley and Slater[74,75] proposed that light could, by damaging retinal tissues, generate free radicals and thereby cause ROP. Interest in light was rekindled by the report by Glass et al[16] that reduction in the neonatal unit illumination reduced the incidence and severity of ROP. This was confirmed by Hommura et al[76] but not by either Ackerman et al[77] or Seiberth et al.[78] To date, all studies suffer from a range of design limitations including low numbers, sequential design, failure to randomise, use of unmasked observers, infrequent ophthalmic examinations.

To overcome the criticisms affecting previous studies a prospective, randomised multicentre study of the effects of light reduction was undertaken on premature babies of birth weights under 1,251 g and gestational ages under 31 weeks.[25] Light reduction was achieved by placing goggles on the infants within the first 24 hours after birth. These goggles reduced light by 97% and UV by 100% and were worn up to 31 weeks PMA or 4 weeks after birth, whichever was the shorter. The cohort was examined for ROP by trained observers. 188 goggled and 173 control infants survived the study period. The mean ambient illumination for the goggled group was 399 lux and 447 lux for the control group. ROP was diagnosed in 54% of the goggled and 58% of the control group, and there was no significant difference in ROP severity between the two groups. Thus, a reduction in ambient-light exposure was not found to alter either the incidence or severity of ROP.

Ophthalmic Sequelae of Preterm Birth

Preterm birth has many effects on the visual system ranging from the extremely subtle to severe vision impairment, and many of these are permanent. The mechanisms by which some of these are caused are not understood, but the following have been implicated: ROP, neurological damage, and prematurity per se. The latter includes, albeit uncomfortably, environmental influences. It is also important to state that more than one factor may be associated with a sequelae—for instance the association of strabismus with prematurity, ROP and neurological damage. Unfortunately it is not always possible to tease out causal relationships and the relative contributions of each purported component to a particular deficit.

The ophthalmic sequelae of preterm birth that might be attributed to being born early alone are generally not visually disabling in contrast to, say, severe ROP or cerebral vision impairment. They can be placed into 3 broad categories (selected references only):

1. Visual functions. A number of reports have shown that ex-preterm children have reduced visual acuity,[79-81] color vision,[82] and contrast sensitivity.[81,83] It is important to emphasize these visual acuity deficits are slight with levels usually lying at the lower border of the normal range.
2. Strabismus. The incidence of strabismus is greatly increased (6-fold by 10 to 12 years) and is related to prematurity per se, ROP and neurological damage.[83,84]
3. Eye size and refractive state. As Fledelius showed about 20 years ago,[85] the eyes of children who were born prematurely exhibit arrested ocular growth. This subtle effect probably accounts for the greatly increased prevalence of myopia in children who were born prematurely.[86-90]

This type of myopia called 'myopia of prematurity' is quite different from myopia, which follows severe ROP.[89] The anterior ocular segments of ex-preterm children are significantly different[90] compared to age-matched normal control children,[91] confirming that myopia that is due to prematurity per se cannot be accounted for by the axial length of the eye but appears to be due to arrested growth of the ocular anterior segment. Another environmental influence, corneal temperature, has been implicated in the development of myopia of prematurity, as preterm infants experience a deficit as a consequence of being removed early from the warmer uterine environment.[92]

Conclusions

Being born early has a wide range of consequences for the developing visual system. While many of these can be attributed to neurological insults or retinopathy of prematurity, this does not account for all, and it is becoming increasingly evident that prematurity on its own impacts the visual system. The lighting environment of the preterm infant is harsh and brightly lit, although there is a recent and encouraging trend to employ lower levels of illumination and to introduce cycling regimens. Light is not a factor in ROP development, but its role in the pathogenesis of other ophthalmic sequelae of preterm birth is not known.

William Silverman—forever on the case—is uncertain that the role of light in ROP is fully elucidated. He also ponders, as we have done here, whether light has an adverse effect on the developing visual system apart from ROP, and even suggests cerebral visual impairment as a possible association of light exposure—"the full story, I suspect, has not yet been told."[93]

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