Hypoxia in the newborn infant

E. O. R. REYNOLDS

From the Department of Paediatrics, University College Hospital and Medical School, London

Disorders of breathing are the commonest causes of hypoxia and death in newborn infants (Chamberlain et al, 1975). The aim of this article is to describe the disorders in which serious hypoxia is most often encountered, the ways in which it can be prevented or treated, and some of the consequences of hypoxia.

Normal cardio-pulmonary adaptation at birth

Many disorders of breathing in the newborn period arise because of failure of normal cardio-pulmonary adaptation. In order to understand the pathogenesis of these disorders it is necessary first to summarize the changes that normally take place in the lungs and circulation at birth.

In fetal life the respiratory centre is not, as was once thought, inactive. Breathing movements in utero, first suspected by Ahlfeld (1888), have been clearly demonstrated in the fetal lamb and subsequently in the human fetus (Boddy and Dawes, 1975). At birth, the lungs replace the placenta as the organ of gas exchange and the activity of the respiratory centre becomes closely adjusted to the metabolic needs of the body. The mechanisms responsible have not been fully worked out but they probably depend on the interplay of a number of different stimuli which regularize and control respiratory neuronal discharge. For example, chilling of the skin at birth and stimulation of receptors near the larynx when liquid is cleared from the airway have both been shown to augment breathing (Johnson et al, 1973; Boddy and Dawes, 1975). Carotid chemoreceptor sensitivity to hypoxia increases greatly and there is some evidence for increased central chemoreceptor sensitivity as well (Purves and Biscoe, 1966).

The fetal lung contains about 30 ml/kg of body weight of liquid. This liquid is a secretion of lung tissue containing very little protein (25 mg/dl) and its composition differs both from that of an ultrafiltrate of plasma and amniotic fluid (Adamson et al, 1969; Olver et al, 1973). At birth the infant makes forceful inspiratory efforts, sometimes -60 cmH₂O (Karlberg et al, 1962), in order to overcome the resistance to the inspiration of air into the liquid-filled lung. The inspiratory efforts not only suck air into the alveoli, they also stretch the alveolar epithelium, which normally has an equivalent pore radius of only 0.5 nm, and is therefore extremely impermeable to solutes (Normand et al, 1971). The pores are stretched to about 3-5 nm in radius (Egan et al, 1975) and the fetal alveolar liquid passes through them, down a protein osmotic pressure gradient, into the interstitial tissue of the lung. From there it is absorbed, largely via lymphatics (Humphreys et al, 1967), into the circulation. Subsequently the pores in the alveolar epithelium contract back towards their fetal size. The secretion of lung liquid stops at birth for reasons that are not understood.

Once breaths of air have been taken, reflex mechanisms come into play which are responsible for rearranging the circulation from the fetal to adult type. In fetal life, the pulmonary arterioles are constricted and only 10 per cent of the cardiac output perfuses the lungs, the remainder shunting from the right to the left side of the circulation through the foramen ovale and ductus arteriosus (Dawes, 1968). When air enters the lung the partial pressure of oxygen (PO₂) rises sharply from the normal fetal level of about 25 mmHg to above 60 mmHg. This increase in PO₂ provides the major stimulus to the large pulmonary arteriolar vasodilatation that occurs at birth (Cook et al, 1963). Another important factor promoting vasodilatation is the development of surface-tension forces in the alveoli which exert radial traction on blood vessels (Cassin et al, 1964). As a result of pulmonary vasodilatation blood flows through the lungs increases and pressure in the left atrium rises. At the same time, right atrial pressure falls slightly, mainly because of cessation of the umbilical circulation. The foramen ovale closes when left atrial pressure rises above right atrial pressure. The ductus arteriosus constricts in response to increasing PO₂ once breathing has started (Kovalčík, 1963). When the foramen ovale and ductus arteriosus have both closed the whole of the cardiac output must pass through the lungs and further oxygenation of the blood can occur.

For several days, sometimes weeks, after birth the
newborn infant remains extremely vulnerable to reopening of the fetal right-to-left shunts. If, due to a pulmonary illness, atelectasis is present and the PO₂ of lung tissue falls, pulmonary vasoconstriction will inevitably follow, and the foramen ovale and ductus arteriosus are likely to reopen. Low pH, common in respiratory illnesses, makes pulmonary vasoconstriction worse (Rudolph and Yuan, 1966). The consequences for the infant may be very serious, since venous blood bypasses the lungs and is directed into the aorta. Reopening of fetal right-to-left shunts is probably the single most important cause of life-threatening hypoxia in the newborn period. Once anatomical closure of these structures has taken place, usually by about two weeks of age, severe hypoxia in association with respiratory illnesses becomes very much less likely.

**Failure of normal cardio-pulmonary adaptation at birth**

**APNOEA AT BIRTH**

By far the commonest causes of failure to breathe at birth are intrapartum asphyxia and excessive maternal analgesia with opiates. Fetal asphyxia evokes gasping but if the asphyxia is more prolonged the central nervous system, including the respiratory centre, becomes depressed and the infant does not respond to the normal stimuli that augment breathing after birth. Opiates have a direct inhibitory influence on the respiratory centre.

The only sure way to resuscitate an infant who shows no sign of breathing is by endotracheal intubation and positive pressure inflation of the lungs. Because the lungs are filled with liquid a high pressure, 25-30 cmH₂O, is needed for the first inflation. This pressure must be applied for about five seconds so that the whole lung becomes evenly inflated. Once the fetal lung liquid has been displaced from the alveoli the lungs can be inflated at lower pressures, about 10-15 cmH₂O. Inflation of the lungs with a face mask or mouth-to-mouth breathing is not so effective as intubation because the necessary transpulmonary pressure is more difficult to achieve and also because gastric distension occurs. Alkali therapy is much less commonly used during resuscitation than in the past. Once an infant is properly oxygenated any metabolic acidosis due to anaerobic glycolysis will usually rapidly resolve, and there are possible dangers associated with the overenthusiastic use of hypertonic bicarbonate solution. For example, it might overload the circulation and increase the risk of cerebral haemorrhage (Simmons et al., 1974). Nevertheless there is still a place for the cautious intravenous infusion of alkali if an infant remains cyanosed and slow to breathe following severe intrapartum asphyxia and in spite of adequate inflation of the lungs with oxygen. Such an infant may also benefit from external cardiac massage.

Infants born apnoeic but with good tone and a normal heart rate can often be encouraged to breathe by peripheral stimulation, and intubation is usually not needed. Warmth must always be provided during resuscitation, to minimize oxygen consumption and prevent hypothermia. If the mother has had excessive opiate analgesia and the infant does not breathe adequately, naloxone should be given intravenously.

**TRANSIENT TACHYPNOEA OF THE NEWBORN (WET LUNG)**

Some infants who remain short of breath for a few hours, or occasionally a day or two, after birth have chest radiographs showing oedema-like changes, with abnormal linear shadows fanning from the hila (Avery et al., 1966). The only adequate explanation for this condition is that it is due to delayed removal of fetal lung liquid. Possibly the affected infants have excessive amounts of the liquid present in their lungs at birth or, if preterm, are unable to exert sufficient transpulmonary pressure during breathing to clear the liquid from their air spaces. Usually oxygen therapy is the only specific treatment required to prevent hypoxia.

**HYALINE MEMBRANE DISEASE (IDIOPATHIC RESPIRATORY DISTRESS SYNDROME OF THE NEWBORN)**

Hyaline membrane disease is probably still the commonest cause of death in infants born in this country (Chamberlain et al., 1975). It affects about 1 per cent of all infants and the incidence increases sharply with decreasing gestation, so that at 27-31 weeks 35-50 per cent of all infants are affected. The illness probably does not occur at term.

The cause of hyaline membrane disease is inadequate production of pulmonary surfactant by type II alveolar pneumonocytes due mainly to immaturity of synthetic mechanisms (Avery and Mead, 1959; Gluck et al., 1972). Asphyxia around the time of birth may worsen the illness by damaging these mechanisms (Reynolds et al., 1965; Gluck et al., 1972). Infants born by Caesarean section before the onset of labour appear to have an increased incidence of the illness (Fedrick and Butler, 1972), possibly because their lungs have not been exposed to the normal increase in plasma cortisol level that occurs at the onset of labour. Whether the infants of diabetic mothers are more likely to develop hyaline membrane disease than other infants remains uncertain, mainly because infants of diabetic mothers seem often to be
short of breath for reasons other than hyaline membrane disease.

In the absence of sufficient synthesis of pulmonary surfactant the alveoli have an abnormal tendency to collapse during expiration and are difficult to inflate during inspiration. The infant therefore has to exert a large inspiratory pressure with every breath. This inspiratory pressure causes the deep retractions of the chest wall which are the most characteristic physical sign of the illness. Often a grunting noise can be heard coming from the larynx. This grunt is due to the partial closure of the glottis which retards alveolar collapse during expiration. Pulmonary vasoconstriction, with reversion to the fetal type of circulation, is particularly severe in infants with hyaline membrane disease, and is secondary to the combined effects of atelectasis, hypoxia and respiratory acidemia. In addition to shunting through reopened fetal channels, right-to-left shunts are present through totally atelectatic areas of lung tissue (Murdock et al, 1970). As much as 80 per cent of the cardiac output may be shunted from the venous to the arterial circulation in the most seriously affected infants (Strang and MacLeish, 1961). Without adequate treatment profound hypoxia ensues, with the eventual development of metabolic acidemia, due to anaerobic glycolysis, and death.

The risk of the development of hyaline membrane disease can be predicted in utero by measurement of the lecithin:phosphatidylglycerol ratio in samples of amniotic fluid (Gluck et al, 1971). If the ratio is above 2, hyaline membrane disease is most unlikely. This test is valuable when a pre-term fetus is at high risk and a balanced judgment has to be reached whether it is safer to deliver the baby or not.

Steroids are capable of stimulating surfactant production by the fetal lung (Avery, 1975). There has, therefore, been much interest in the possibility of preventing hyaline membrane disease by administering steroids to the mother antenatally. Controlled trials suggest that this treatment is effective, particularly if the infant is at 32 weeks of gestation or less, but the effect is rather small (Liggins and Howie, 1972). If the mother is hypertensive steroids are contraindicated. The exact role of steroid prophylaxis of hyaline membrane disease remains uncertain, and more information is required.

The treatment of established hyaline membrane disease has become very much easier in recent years and mortality rates reported by major centres have fallen from 35 to 50 per cent 10 years ago to less than 10 per cent (Reynolds, 1975) (fig 1). The main reason for this improvement has been the development of effective means for controlling oxygen therapy and preventing hypoxia.

Instead of taking samples of arterial blood inter-

mittently for blood gas analysis it is now possible to insert a catheter with a miniaturized oxygen electrode built into its tip into the aorta via the umbilical artery (Conway et al, 1976). Aortic PaO2 is continuously displayed and recorded (fig 2). The correct inspired oxygen concentration can therefore be selected with much greater precision than in the past and a course can be steered between the dangers of hypoxia (brain damage and death) on the one hand and hyperoxia (retrolental fibroplasia and blindness in preterm infants) on the other. A PaO2 of 65 mmHg is probably a reasonable level to aim for.

The transcutaneous estimation of PaO2 has also recently been shown to be feasible (Huch et al, 1974). If an oxygen electrode is applied to the skin and heated, capillary blood flow increases and transcutaneous oxygen tension (tcPO2) correlates well with PaO2 under most circumstances. In seriously ill infants with a poor skin blood flow tcPO2 underestimates PaO2 and should not be relied upon. The continuous recording of PaO2 and tcPO2 is extremely valuable in all infants with significant respiratory illness.
Infants with hyaline membrane disease, whose PaO₂ is falling in spite of an increasing inspired oxygen concentration, can be treated with continuous positive airway pressure (CPAP) (Gregory et al, 1971). The aim is to raise the pressure in the infant's airway so that lung collapse is, partly at least, prevented while spontaneous breathing continues. An adequate indication for initiating CPAP is a PaO₂ below 60 mmHg in an infant breathing more than 60 per cent oxygen. PaO₂ almost always improves when CPAP is started. Various methods have been employed, including endotracheal tubes, head boxes, face masks, nasal prongs and negative pressure tanks. Possibly the face mask is the method of choice for relatively mildly affected infants (Allen et al, 1975) and endotracheal tubes for worse affected ones (Gregory et al, 1971). Pressures of up to about 6 cmH₂O can be applied with the mask, and 10 cmH₂O with the endotracheal tube.

Infants who do not maintain a satisfactory PaO₂ (> 35-50 mmHg) when being treated with CPAP or who are tending to become apnoeic need mechanical ventilation. In the past the mortality rate of infants ventilated for hyaline membrane disease was high and many died from bronchopulmonary dysplasia (see page 139). With improved ventilator techniques the outcome has greatly improved (Reynolds, 1974; 1975), and bronchopulmonary dysplasia has become a rarity.

No infant born at a gestational age greater than about 28 weeks should now die or be damaged as a result of hypoxia due to hyaline membrane disease.

**PERSISTENT FETAL CIRCULATION OF UNKNOWN AETIOLOGY**

In most pulmonary illnesses hypoxia is due to a combination of interference with gas exchange in the lung with a variable degree of secondary right-to-left shunting through reopened fetal channels. In a small minority of hypoxic infants no pulmonary pathology (or congenital abnormality) can be demonstrated, yet the PaO₂ remains low even though the infant is breathing a high concentration of oxygen, indicating right-to-left shunting of blood. Sometimes the preductal PaO₂ is much higher than the postductal PaO₂, which implies that there is a much larger shunt through the ductus arteriosus than through the foramen ovale. The condition has been called persistent fetal circulation, or persistent transitional circulation. The aetiology is unknown. Possibly some
vasoactive substance is maintaining pulmonary vaso-
constriction after birth. Spontaneous recovery takes
place within a few days if the infant is kept properly
oxygenated. Tolazoline, which dilates pulmonary
blood vessels more than systemic vessels, is often
effective in raising the PaO₂ and can be given by
constant infusion if required.

**RECURRENT APNOEA IN PRETERM INFANTS**

Most infants born at less than 32 weeks of gestation
have periodic breathing and short attacks of apnoea
even if their lungs are normal and they are well in all
other ways. Sometimes, prolonged apnoeic attacks
occur, particularly in the smallest infants, causing
serious hypoxia. The reason for the irregular
breathing and apnoea is inadequate development of
various aspects of the control of breathing. Apnoeic
attacks can be detected by using monitoring devices
set to sound after 10 to 15 sec of apnoea. Peripheral
stimulation will almost always start the infant
breathing again.

Small preterm infants often have a PaO₂ of about
50 mmHg while breathing air. Increasing the inspired
oxygen concentration slightly, to 23-25 per cent,
raises the PaO₂ to about 70 to 80 mmHg and reduces
the incidence of apnoea. Increases in inspired
oxygen concentration should, however, never be
given without measurement of PaO₂. The risk of
raising the PaO₂ to a dangerously high level (> 100
mmHg) is very great in infants with normal lungs,
and it is these infants who are most at risk for retro-
lental fibroplasia. The continuous measurement of
tcPO₂ may prove to be a valuable aid to therapy.

Other methods of treatment include CPAP and the
use of theophylline. Continuous positive airway
pressure applied through a face mask (or some other
device) at a pressure of 3-4 cmH₂O stimulates
stretch receptors in the lung or chest wall and is an
effective way of reducing the frequency of apnoea
(Kattwinkel et al, 1975). Higher pressures must be
avoided, because the lungs are normal and easily
become overdistended, with the risk of pneumo-
thorax or obstruction of the circulation.
Theophylline is a respiratory stimulant which
reduces the incidence of apnoeic attacks (Shannon et
al, 1975).

Infants whose breathing fails in spite of the
methods described above can usually be me-
chanically ventilated through a face mask (Allen et al,
1975), thus avoiding the difficulties associated with
prolonged intubation in very preterm infants.

**Congenital malformations**

By comparison with most other disorders causing
hypoxia in newborn infants, congenital mal-
formations are rare. The commonest ones affecting
the lungs are diaphragmatic hernia and hypoplastic
lungs. Many types of congenital heart disease also
cause hypoxia, because of right-to-left shunting of
blood, poor peripheral perfusion, or both. Common
congenital heart lesions causing serious hypoxia
include tricuspid atresia, transposition of the great
vessels, the hypoplastic left heart syndrome, total
anomalous pulmonary venous damage and severe
forms of Fallot's tetralogy.

**Acquired disorders**

**PNEUMOTHORAX**

Spontaneous pneumothoraces, probably due to the
large inspiratory efforts made immediately after
delivery, occur in about 1 per cent of all infants
(Steele et al, 1971). Usually these pneumothoraces
are small and resolve spontaneously. More serious
pneumothoraces occur as a complication of mecon-
ium aspiration. Drainage is often required, in order
to avoid dangerous hypoxia or obstruction of the
circulation. Pneumothorax is also a relatively com-
mon hazard of the use of CPAP or mechanical
ventilation, particularly for the treatment of hyaline
membrane disease, with an incidence of about 20 per
cent. Urgent treatment is usually required, but the
lung almost always heals within a few days, as the
underlying illness resolves.

**MECONIUM ASPIRATION**

Intrapartum asphyxia causes gasping and evacuation
of the bowel. Hence meconium can be aspirated into
the upper airways. Meconium aspiration is particu-
larly commonly seen in postterm infants, and it is
very unusual in infants of less than 37 weeks of
gestation. Immediate pharyngeal, and if necessary,
endotracheal, suction is required at birth, to prevent
the meconium from being inhaled into the small air-
ways. If large amounts of meconium are inhaled
deeply into the lung the infant becomes extremely
hypoxic, and is very difficult to treat. Mechanical
ventilation is needed and tolazoline has been found
to be useful in improving oxygenation. In surviving
infants, full recovery takes place within a week.

**HAEMORRHAGIC PULMONARY OEDEMA AND
MASSIVE PULMONARY HAEMORRHAGE**

This condition is regarded as a major cause of death
in about 9 per cent of neonatal necropsies (Fedrick
and Butler, 1971). It presents clinically as profound
collapse, with blood-stained fluid pouring out of the
trachea. The fluid is usually a filtrate of plasma, with
a small admixture of whole blood (Cole et al, 1973).
in other words it is haemorrhagic pulmonary
oedema fluid, formed as a result of increased pul-
monary capillary pressure. The likely reason for the increase in pressure is that a severe asphyxial episode (of whatever aetiology) causes acute left heart failure, or centralization of the circulation. Any additional factors that tend to raise filtration pressure will increase the risk of haemorrhagic pulmonary oedema, for example hypoproteinaemia, as in severe rhesus haemolytic disease. Disorders of haemostasis are often found and probably result from the underlying asphyxial episode that caused the haemorrhagic oedema. A bleeding tendency encourages continued haemorrhage from ruptured capillaries. Treatment by mechanical ventilation, if undertaken promptly, is often successful, and the outlook for affected infants has improved greatly in the past few years.

By comparison with haemorrhagic pulmonary oedema frank bleeding into the lung is rare and probably occurs only in association with profound haemostatic failure or severe pneumonia.

**HYDROPS FETALIS**
Hydrops fetalis is usually due to severe rhesus iso-immunization. Breathing is grossly impaired by oedema of the larynx, lungs and chest wall, together with a reduction of thoracic volume due to the presence of the enlarged liver and spleen and ascites. Unless treated by mechanical ventilation from birth the infants become very severely hypoxic. Many now survive.

**PNEUMONIA**
The commonest organism causing severe pneumonia in the immediate newborn period is the group B β-haemolytic streptococcus acquired before or during delivery from the mother's genital tract. The clinical presentation and radiological appearance sometimes mimic hyaline membrane disease very closely (Ablow et al, 1976). Examination of gastric aspirate for organisms is helpful in making an immediate diagnosis. If any suspicion exists that an infant is infected with the group B streptococcus, or any other organisms, such as *E. coli*, at birth, immediate treatment with antibiotics, before the results of cultures are available, is mandatory. Once unequivocal clinical evidence of infection has developed, the chances of survival are poor. A suitable combination of antibiotics is penicillin and gentamicin.

**CHRONIC LUNG DISEASE**
In 1967, Northway et al gave the first clear description of severe lung fibrosis following mechanical ventilation for hyaline membrane disease. They called the condition 'bronchopulmonary dysplasia' and suggested that it was caused by pulmonary oxygen toxicity. In the same year it was shown that the development of bronchopulmonary dysplasia was not associated with persisting deficiency of pulmonary surfactant (Hawker et al, 1967). The main lesions consist of severe disruption of terminal airways, with fibroblastic proliferation obstructing their lumina and spreading out into the surrounding tissue. The presence of these lesions correlates with the use of very high peak airway pressures (35–60 cmH₂O) for more than two days during mechanical ventilation, but not with the inspired oxygen concentration (Taghizadeh and Reynolds, 1976). It has therefore been concluded that the cause of these lesions is mechanical trauma to the lung. If ventilator techniques are used that maintain alveolar inflation without the use of high peak airway pressures bronchopulmonary dysplasia is very rarely seen (Reynolds, 1974; Reynolds and Taghizadeh, 1974). Convincing evidence that pulmonary oxygen toxicity plays any important part in pathogenesis is very hard to find although it may have a minor role (Taghizadeh and Reynolds, 1976). Surprisingly, the lungs of infants who survive appear to recover completely to normal, although they may take months to do so (Stahlman et al, 1973).

Another cause of chronic lung disease in newborn infants is the 'Wilson-Mikity syndrome' (Wilson and Mikity, 1960). This condition affects greatly preterm infants, who become somewhat hypoxic when they are several days old and have a chest radiological appearance showing streaky shadows due to atelectasis or fibrosis interspersed with areas of compensatory or obstructive emphysema. Before 32 weeks of gestation, infants are unable to protect the upper airway, because they have no adequate cough reflex. In addition, the fine airways are narrow, poorly supported with cartilage (Burnard et al, 1965), and easily become obstructed. Probably the Wilson-Mikity syndrome is not a clinical entity but results from any disorder that causes widespread uneven obstruction of airways in greatly preterm infants. For example, aspiration of feed, or retained pulmonary secretions in infants ventilated through endotracheal tubes, can both produce radiological appearance identical to that originally described. After a protracted course, most affected infants recover.

**Consequences of severe hypoxia**
Lack of oxygen causes anaerobic glycolysis, with the development of a metabolic acidosis due to accumulation of lactic acid. The combination of hypoxia and acidosis impairs cardiac function (Downing et al, 1965) and increases pulmonary vascular resistance (Rudolph and Yuan, 1966). In addition, severe hypoxia causes interference with the production of clotting factors from the liver and may also initiate...
disseminated intravascular coagulation. A tendency to bleed is common in any severely hypoxic infant (Chessells and Wigglesworth, 1972).

There is a strong association between hypoxia and intraventricular haemorrhage—a very common cause of death in preterm infants. The mechanism of intraventricular haemorrhage is probably that an asphyxial episode produces an increase in intravascular pressure which ruptures vulnerable vessels in the germinal matrix (Cole et al., 1974; Hambleton and Wigglesworth, 1976). Hypoxia is also a major factor in the pathogenesis of necrotizing enterocolitis (Santulli et al., 1975). This illness often follows severe asphyxia at birth, or interference with blood flow to or from the gut by the use of umbilical arterial or venous catheters (Bunton et al., 1977). The pathological results of hypoxia, including its effect on the brain, are dealt with elsewhere in this symposium.

**Conclusion**

Hypoxia in newborn infants is becoming much easier to prevent, detect and treat. Nevertheless the successful management of potentially hypoxic fetuses and newborn infants remains the major challenge to all physicians concerned with perinatal care. What is at stake is not only that sick infants should survive, but equally or more importantly that the survivors should be normal children. Recent follow-up studies show that this aim can, with few exceptions, now be achieved (Stewart and Reynolds, 1974; Davies and Stewart, 1975; Durbin et al., 1976).

**References**


Gregory, G. A., Kitterman, J. A., Phibbs, R. H., Tooley,
Hypoxia in the newborn infant


