

Placental Gas Exchange

How do the placenta and the lungs compare as gas exchanging units?

Gas exchange in the placenta is much less efficient than in a lung. This is because the minimum diffusion distance is much larger (eg 3.5 μm vs 0.5 μm in the lung) and the permeability of the blood-blood barrier is much lower than the permeability of the blood-gas barrier in the lung.

The total surface area of the placenta at term is about 16 m² as compared to 50 to 60 m² in the adult lung. The surface area is about a quarter of the size but it transfers only one-tenth of the oxygen. The inefficiency of the gas exchange is compensated for by a relatively much larger surface area.

In summary, as compared to the adult lung, the placenta is inefficient at gas exchange because of larger diffusion distance **and** lower gas permeability.

The foetus requires an increasing oxygen supply as it grows. How are these increased oxygen needs met?

The factors involved are

- Increased maternal blood supply to the placenta (Uterine flow increases 20 fold during pregnancy)
- Increased foetal blood supply to the placenta
- Presence of foetal haemoglobin which has a higher oxygen affinity than maternal HbA
- Higher [Hb] concentration in the foetus (40% higher than in adult)
- The Double Bohr Effect.

What is the uterine blood flow at term?

About 500-750 ml/min and 85% of this goes to the placenta. Note that the uterine supply to the placenta is not autoregulated and flow is pressure dependent.

What vessels supply foetal deoxygenated blood to the placenta?

Umbilical arteries.

What is the umbilical artery flow at term?

The foetal cardiac output at term is about 1,000 ml/min: from 25 to 55 percent of this goes to the placenta.

What is the special feature of foetal haemoglobin? How does it assist the foetus?

It has a lower P₅₀ (18 to 20 mmHg) than adult Hb (26.6 mmHg). This means foetal haemoglobin has a *higher oxygen affinity* and this assists it to load oxygen in the placenta while maternal haemoglobin is unloading oxygen. It has a higher saturation at a given pO₂ than adult haemoglobin eg foetal Hb has a saturation of 80% at a pO₂ of 30 mmHg.

Why does foetal haemoglobin have such a low P50?

The higher P₅₀ of adult haemoglobin in red cells is due to the right shift that occurs in the presence of high levels of 2,3 DPG in the red cell. The 2,3 DPG binds to the β -chains of HbA (especially *deoxy* HbA) to cause this effect. Several amino acids are involved in the binding and each tetramer of adult haemoglobin binds one molecule of 2,3 DPG.

Foetal Hb is a tetramer: $\alpha_2\gamma_2$. There are no β -chains so HbF is insensitive to a shift due to 2,3 DPG binding.

How long does foetal haemoglobin persist after birth?

At birth about 80% of the neonate's haemoglobin is HbF. This decreases rapidly so that by the age of 6 months less than 5% of the baby's haemoglobin is HbF. Only very small amounts of HbF are normally present in adults (<1% of total haemoglobin in adults).

What is the 'double Bohr effect'?

How does this affect oxygen uptake by the foetus?

The term *double Bohr effect* refers to the situation in the placenta where the Bohr effect is operative in both the maternal and foetal circulations.

The increase in pCO₂ in the maternal intervillous sinuses assists oxygen unloading. The decrease in pCO₂ on the foetal side of the circulation assists oxygen loading. The Bohr effect facilitates the reciprocal exchange of oxygen for carbon dioxide.

The double Bohr effect means that the oxygen dissociation curves for maternal HbA and foetal HbF move apart (ie in opposite directions).

What are the special factors which assist carbon dioxide transfer across the placenta?

The important factors relevant to the placenta are:

- Maternal hyperventilation results in a low maternal pCO₂ which increases the gradient favouring CO₂ transfer
- A double Haldane effect occurs and this is unique to the placenta.

What is the [Hb] at birth?

This is typically high: about 17 to 18 g/dl.

In what ways does the haemoglobin change in the first year after birth?

The major changes are:

- Decrease in [Hb] (*physiological anaemia of infancy*)
- Rapid decrease then elimination of HbF (as discussed above)
- Increased production of adult haemoglobin (HbA) to replace HbF.

After birth, the arterial pO₂ (and Hb saturation) in the neonate is much higher and erythropoietin levels consequently drop to undetectable levels. Red cell production is markedly decreased and [Hb] falls. The decrease in oxygen delivery is partially compensated by a shift of the haemoglobin oxygen dissociation curve to the right as HbF is replaced by HbA and red cell 2,3 DPG levels rise.

Finally, [Hb] levels fall far enough to cause increased levels of erythropoietin and red cell production increases. The physiological anaemia of infancy lasts for about 6 months.

Can you tell me what are the pO₂, SO₂ and pCO₂ values in the uterine vessels and in the umbilical vessels?

Typical values are:

Maternal circulation

- Uterine artery: pO₂ 100mmHg (SO₂ 98%); pCO₂ 32mmHg
- Uterine vein: pO₂ 40mmHg (SO₂ 75%); pCO₂ 45mmHg

Foetal circulation

- Umbilical artery: pO₂ 18mmHg (SO₂ 45%); pCO₂ 55mmHg
- Umbilical vein: pO₂ 28mmHg (SO₂ 70%); pCO₂ 40mmHg

(see diagram on p255)

Can you outline the oxygen balance across the placenta?

The points to consider are:

- Oxygen is delivered to the placenta from the maternal uterine artery and the foetal umbilical artery
- Oxygen is taken away from the placenta in the uterine vein and the umbilical vein.
- Placental oxygen consumption is large and is equal to the difference between the oxygen delivered to the placenta and the oxygen taken away from the placenta. Placental oxygen consumption is about 10 mls/kg/min. The placenta is typically one seventh the weight of the foetus so placental oxygen consumption is about 5 mlsO₂/min.
- Foetal oxygen consumption at term is almost 5 mls O₂/kg/min or a total of about 15 to 17 mlsO₂/min. It is equal to the difference between the oxygen delivery to the foetus in the umbilical vein and the oxygen return to the placenta in the umbilical artery.
- The oxygen consumption of the placenta (and myometrium) is equal to the total oxygen delivered to the placenta and uterus less the total oxygen taken away from the placenta and uterus.

Oxygen flow is equal to oxygen content multiplied by the blood flow. In any vessel, oxygen content is equal to $([Hb] \times SO_2 \times 1.34)$. The calculations to determine oxygen balance in the placenta require values for 12 parameters. These are listed below with some typical values:

Mother	
1. Uterine blood flow	600 mls/min
2. Maternal [Hb]	120 g/l (low due 'physiological anaemia')
3. SO ₂ in the uterine artery	98%
4. SO ₂ in the uterine vein	75%
5. pO ₂ in uterine artery	100 mmHg
6. pO ₂ in uterine vein	40 mmHg
Foetus	
7. Umbilical blood flow	300 mls/min
8. Foetal [Hb]	170 g/l
9. SO ₂ in umbilical artery	45% (despite low pO ₂ due high O ₂ affinity)
10. SO ₂ in umbilical vein	70% (despite low pO ₂ due high affinity)
11. pO ₂ in umbilical artery	18 mmHg
12. pO ₂ in umbilical vein	28 mmHg

Oxygen supply to the placenta (from mother and foetus) must be equal to the oxygen flow away from the placenta plus the oxygen consumption of the placenta and myometrium. Also, the results of our calculations can be checked to see if they agree with our predictions for foetal oxygen consumption and placental oxygen consumption.

Using the typical values above:

Oxygen delivery to the placenta (and uterus)

$$\begin{aligned}
 &= \text{Oxygen delivery in uterine artery} + \text{Oxygen delivery in umbilical artery} \\
 &= [(120 \times 1.34 \times 0.98) + (0.03 \times 100)] \times 0.6 + [(170 \times 1.34 \times 0.45) + (0.03 \times 18)] \times 0.3 \\
 &= (96.4 + 30.9) \text{ mlsO}_2/\text{min} \\
 &= 127.3 \text{ mls O}_2/\text{min}
 \end{aligned}$$

Oxygen carried away from the placenta (and uterus)

$$\begin{aligned}
 &= \text{Oxygen flow in uterine vein} + \text{Oxygen flow in umbilical vein} \\
 &= [(120 \times 1.34 \times 0.75) + (0.03 \times 40)] \times 0.6 + [(170 \times 1.34 \times 0.70) + (0.03 \times 28)] \times 0.3 \\
 &= (73.1 + 48.1) \text{ mlsO}_2/\text{min} \\
 &= 121.2 \text{ mlsO}_2/\text{min}
 \end{aligned}$$

Foetal oxygen consumption

$$= \text{Oxygen flow in umbilical vein} - \text{oxygen flow in umbilical artery}$$

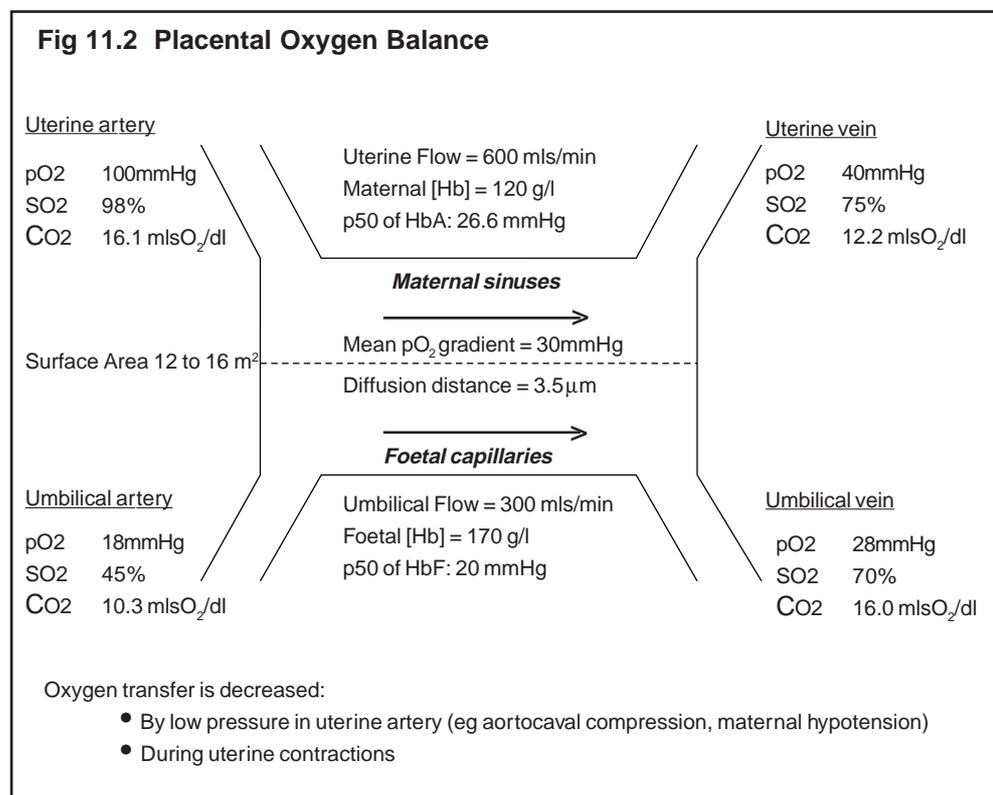
= 48.1 - 30.9
= 17.2 mls/min

Placental & myometrial oxygen consumption

= Oxygen delivery to placenta - Oxygen carried away from placenta
= 127.3 - 121.2
= 6.1 mls/min

Note that the combination of a low maternal [Hb] and the high foetal [Hb] requires either that the uterine artery flow is significantly higher than umbilical artery flow or that the oxygen extraction ratio in the placenta is high (or some combination of these two circumstances).

(A complete or a consistent set of values for the above calculations is difficult to find in the literature. Human data is difficult to obtain and values derived from animal work are sometimes quoted.)

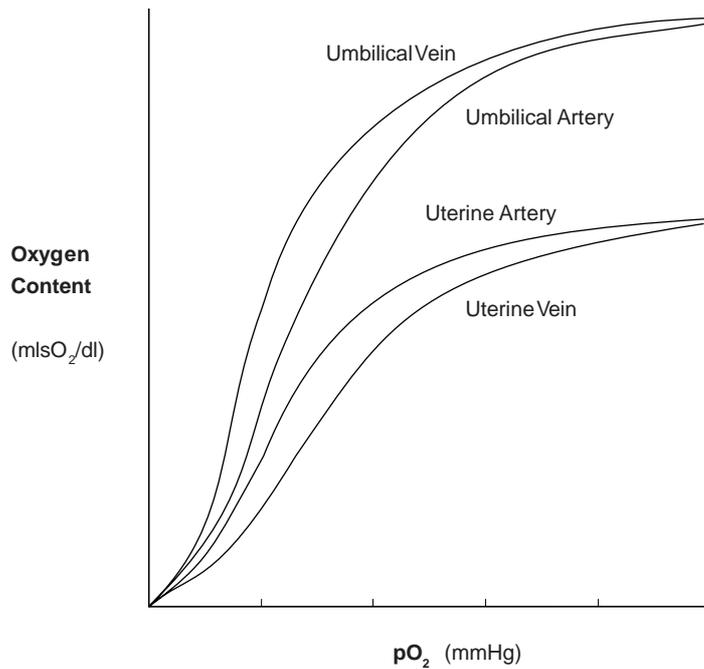


Can you draw the oxygen dissociation curves for maternal and foetal haemoglobin indicating values in the placenta? (using oxygen content on the y-axis)

This involves drawing four dissociation curves because the curves for maternal HbA and foetal HbF are different and each requires a second curve to demonstrate the change in affinity due to the Bohr effect (ie the 'double Bohr' effect)

The use of oxygen content on the y-axis allows clear demonstration of the differences in content due to the low [Hb] of the mother and the high [Hb] of the foetus.

The position of the maternal ODC tends to be similar to that normal adult HbA. The low maternal pCO₂ tends to shift the curve to the left but the effect of this is minimised because maternal arterial pH usually returns to the normal range. An increased maternal red cell 2,3 DPG also shifts the curve rightward.

Fig 11.3 Oxygen Dissociation Curves for Mother and Foetus

Both maternal (HbA) and foetal (HbF) oxygen dissociation curves undergo a change in position due to the Bohr effect. This is known as the '**double Bohr effect**' and is one of the factors that facilitates oxygen transfer from maternal blood to foetal blood.

(The curves above are drawn with a little artistic licence so actual values are not indicated on the x and y axes. The actual oxygen contents in each vessel in any individual person depends on the [Hb] and the oxygen saturations.)