Biochemistry

Unit 6 · Lesson 2 · Building lipids, clearing nitrogen

The notes for Lesson 2 of Unit 6: chapters 6.4 to 6.6 of the unit book, with their figures, worked examples, exam traps and quizzes, in one file. The full unit book, with every chapter, the exam question bank and the glossary, is linked at the end.

Lesson 2 of 3 | 3 chapters | Chapters 6.4 to 6.6

About these notes

These are the notes for **Lesson 2 · Building lipids, clearing nitrogen** of the University free n easy video lessons on Biochemistry Unit 6, Lipid, Amino Acid and Nucleotide Metabolism. They are chapters 6.4 to 6.6 of the unit book, unchanged, so a page here is the same page in the full book.

6.4 Synthesis of triacylglycerols, phospholipids and cholesterol

Fatty acids made in Chapter 6.2 are not stored free. Cells attach them to glycerol to make storage fat (**triacylglycerol**, TAG) and membrane lipids (**glycerophospholipids**), and the liver builds **cholesterol** from acetyl-CoA. Their structures are in **Unit 3, Phospholipids** and **Cholesterol and steroids**.

Triacylglycerol: the phosphatidic acid route

1. **Glycerol 3-phosphate** comes from dihydroxyacetone phosphate of glycolysis (glycerol 3-phosphate dehydrogenase, NADH) in adipose tissue and liver, or from free glycerol by **glycerol kinase**, which liver has and adipose tissue has very little of.
2. Two acyltransferases add two fatty acyl-CoA at C-1 and C-2, giving **phosphatidic acid** (phosphatidate), the branch point for TAG and phospholipids.
3. **Phosphatidate phosphatase** (lipin) removes the phosphate, giving 1,2-**diacylglycerol** (DAG).
4. **DAG acyltransferase** (DGAT) adds the third acyl-CoA, giving TAG.

The liver exports TAG in VLDL; adipose tissue stores it as fat droplets. In the intestine, TAG is rebuilt from 2-monoacylglycerol, a different route used after digestion.

Glycerophospholipids: two ways to attach the head group

Both ways use **CTP** to make an activated intermediate. Either the DAG part or the head group carries the CDP:

- **CDP-alcohol route** (the Kennedy pathway). Choline is phosphorylated, then activated as **CDP-choline**; CDP-choline + DAG → **phosphatidylcholine** (lecithin) + CMP. Ethanolamine follows the same route to phosphatidylethanolamine (a cephalin). In the liver, phosphatidylethanolamine can also be methylated three times by S-adenosylmethionine (SAM) to phosphatidylcholine.
- **CDP-diacylglycerol route.** Phosphatidate + CTP → **CDP-DAG**, which reacts with inositol to give phosphatidylinositol, or with glycerol 3-phosphate to give phosphatidylglycerol and then cardiolipin, the lipid of the inner mitochondrial membrane.

Phosphatidylserine is made in mammals by swapping the head group of an existing phospholipid for serine.

Cholesterol: from acetyl-CoA to a C27 sterol

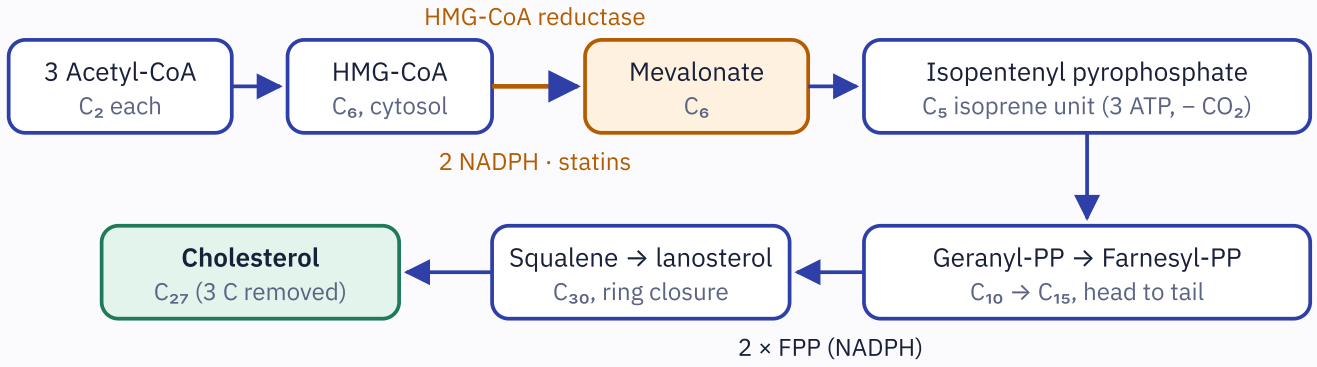


Figure 6.4.1 Cholesterol synthesis in four stages, with the carbon count at each stage. The orange step, HMG-CoA reductase, is the rate-limiting step and the target of statin drugs.

1. **Acetyl-CoA → mevalonate** (cytosol and ER). Two acetyl-CoA make acetoacetyl-CoA; cytosolic HMG-CoA synthase adds a third to give HMG-CoA. **HMG-CoA reductase**, an ER membrane enzyme, reduces it to mevalonate with 2 NADPH. This is the committed, rate-limiting step.
2. **Mevalonate → activated isoprene units.** Three ATP are used to phosphorylate and decarboxylate mevalonate to **isopentenyl pyrophosphate** (C5), which is isomerised to dimethylallyl pyrophosphate.
3. **Condensation.** C5 + C5 → geranyl pyrophosphate (C10); + C5 → **farnesyl pyrophosphate** (C15). Two farnesyl pyrophosphates join head to head, with NADPH, to make **squalene** (C30).

4. **Ring closure and trimming.** Squalene is epoxidised (O_2, NADPH) and cyclised to **lanosterol**, the first sterol. A series of about 20 further reactions remove three methyl carbons and move a double bond to give cholesterol (C27).

Regulation. HMG-CoA reductase is controlled at every level: the transcription factor **SREBP** raises its gene expression when cell sterol is low; high sterol speeds the enzyme's breakdown; AMPK phosphorylation inactivates it; insulin favours and glucagon opposes its activity. **Statins** (atorvastatin, rosuvastatin) are competitive inhibitors of HMG-CoA reductase, with a part that resembles mevalonate, and lower blood LDL cholesterol.

WORKED EXAMPLE

Question (4 marks). How many acetyl-CoA are needed to make one squalene, and how many carbons are lost on the way from squalene to cholesterol?

1. Each mevalonate uses 3 acetyl-CoA (6 carbons) and loses 1 CO_2 to give one C5 isoprene unit.
2. Squalene is C30 = 30 / 5 = **6 isoprene units** = 6 mevalonate = **18 acetyl-CoA**.
3. Cholesterol is C27, so **3 carbons** are removed after lanosterol.

EXAM TRAPS

- Phosphatidic acid is the shared precursor of TAG and glycerophospholipids; DAG is not phosphorylated to make TAG.
- Cholesterol needs NADPH, not NADH, and the rate-limiting enzyme is HMG-CoA reductase, not HMG-CoA synthase.
- Squalene is C30; cholesterol is C27.

CHECK YOURSELF

– REMEMBER **Name the activated intermediate that carries choline to DAG.** 1 mark

CDP-choline.

– UNDERSTAND **Why does adipose tissue depend on glycolysis to make TAG?** 3 marks

It has very little glycerol kinase, so it cannot reuse free glycerol; glycerol 3-phosphate must come from dihydroxyacetone phosphate of glycolysis.

– APPLY **How many NADPH are used from 3 acetyl-CoA to one isopentenyl pyrophosphate?** 2 marks

2 NADPH, at HMG-CoA reductase (plus 3 ATP for the phosphorylations).

– ANALYZE **Statins lower LDL in blood even though they act inside liver cells. Explain.** 4 marks

Lower cholesterol synthesis lowers liver sterol, which activates SREBP; SREBP raises LDL-receptor production, so the liver takes up more LDL from blood.

– REMEMBER **Which lipid is made from CDP-DAG and is found in the inner mitochondrial membrane?** 1 mark

Cardiolipin.

BEYOND THE SYLLABUS

The isoprenoid branch from farnesyl pyrophosphate also makes coenzyme Q, dolichol and the prenyl groups attached to Ras proteins. Plants and many bacteria make isopentenyl pyrophosphate by a different, non-mevalonate (MEP) route, which is the target of engineering for artemisinin and other terpenoid drugs. Search "MEP pathway terpenoid engineering". Not for the exam.

6.5 Amino acid catabolism: transamination and deamination

The body cannot store extra amino acids. Those not needed for proteins and other molecules are broken down, and breaking one down has two parts: remove the amino group, then burn or reuse the carbon skeleton. The amino group is removed in two moves. **Transamination** passes it to α-ketoglutarate, collecting nitrogen from most amino acids as glutamate. **Oxidative deamination** of glutamate then releases it as ammonium (NH_4^+), which the liver turns into urea (Chapter 6.6). The carbon skeletons end up as pyruvate or TCA cycle intermediates.

You need: amino acid structures from **Unit 2, Amino acids: structure and classification**, and the TCA cycle from **Unit 5**.

Transamination

An **aminotransferase** (transaminase) moves the α-amino group of an amino acid onto an α-keto acid. The amino acid becomes a keto acid and the keto acid becomes an amino acid:



- The coenzyme is **pyridoxal phosphate (PLP)**, from vitamin B_6. PLP accepts the amino group (becoming pyridoxamine phosphate) and then hands it to the keto acid, a **ping-pong** mechanism.
- The reaction is freely reversible ($\Delta G^{\circ\prime}$ close to zero), so the same enzymes also make non-essential amino acids.
- Most aminotransferases use α-ketoglutarate as the acceptor, so nitrogen from many amino acids is funnelled into one molecule, **glutamate**. Lysine and threonine are the usual exceptions that are not transaminated.

Two aminotransferases matter clinically:

- **Alanine aminotransferase (ALT**, older name SGPT): alanine + α-ketoglutarate ⇌ pyruvate + glutamate.
- **Aspartate aminotransferase (AST**, older name SGOT): aspartate + α-ketoglutarate ⇌ oxaloacetate + glutamate.

Both are inside cells, so high levels in serum mean cell damage. ALT is more specific for liver; AST is also found in heart and muscle. A "liver function test" report from any Indian lab lists both.

Oxidative deamination by glutamate dehydrogenase

In liver mitochondria, **glutamate dehydrogenase (GDH)** removes the amino group of glutamate as free ammonium:



GDH is unusual because it can use either NAD^+ or $NADP^+$. It is allosterically activated by ADP (low energy: burn amino acids) and inhibited by GTP. Transamination and GDH working together are called **transdeamination**: α-ketoglutarate is regenerated, ready to collect the next amino group.

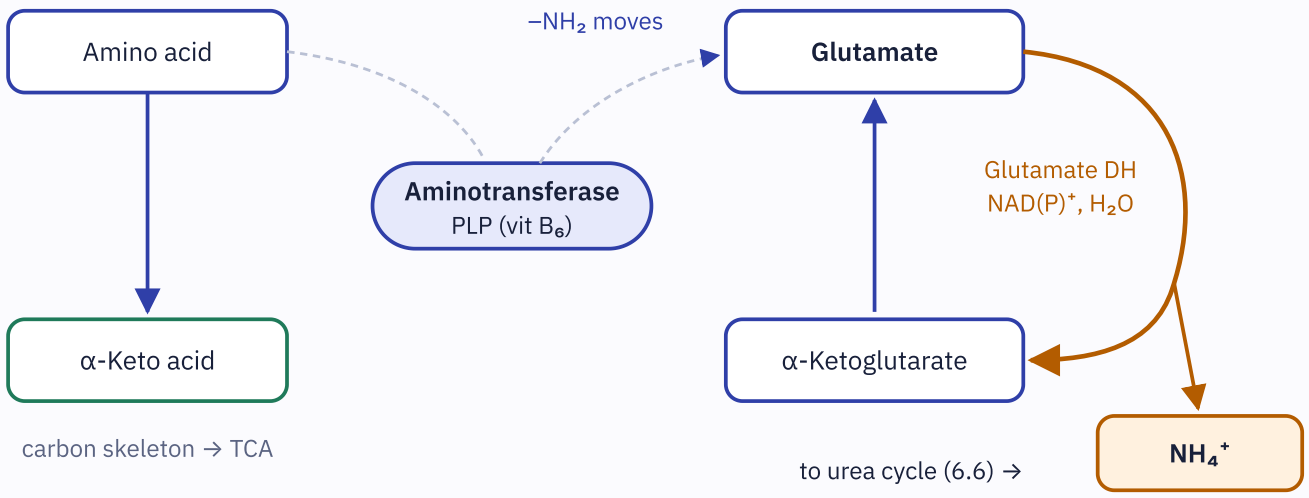


Figure 6.5.1 Transdeamination. The aminotransferase moves the amino group to α-ketoglutarate; glutamate dehydrogenase releases it as NH_4^+ and gives back α-ketoglutarate. Notice that α-ketoglutarate goes round in a loop and is not used up.

Other ways to remove or carry nitrogen

- **Non-oxidative deamination.** Serine and threonine are deaminated by PLP-dependent dehydratases (serine dehydratase gives pyruvate + NH_4^+).
- **Amino acid oxidases.** L- and D-amino acid oxidases (flavoproteins, mainly in liver and kidney peroxisomes) deaminate some amino acids, producing H_2O_2. D-amino acid oxidase removes D-amino acids from bacterial cell walls in food.
- **Carrying ammonia to the liver.** Free NH_4^+ is toxic, so tissues carry it safely. Most tissues add it to glutamate as **glutamine** (glutamine synthetase, uses ATP); liver and kidney release it again with glutaminase. Muscle uses the **glucose–alanine cycle**: pyruvate picks up nitrogen as alanine, alanine goes to the liver, gives its nitrogen for urea, and its pyruvate becomes glucose that returns to muscle.

Decarboxylation and the fate of carbon skeletons

Decarboxylation of amino acids by PLP-dependent decarboxylases removes the carboxyl as CO_2 and makes biologically active amines: histidine → **histamine**; glutamate → **GABA** (γ-aminobutyrate, a brain neurotransmitter); 5-hydroxytryptophan → **serotonin**; DOPA → **dopamine**, the precursor of noradrenaline and adrenaline.

After the amino group is gone, the carbon skeletons of the 20 amino acids enter metabolism at just seven molecules:

ENTRY POINT	AMINO ACIDS	TYPE
Pyruvate	Ala, Gly, Ser, Cys, Thr, Trp	Glucogenic

ENTRY POINT	AMINO ACIDS	TYPE
α-Ketoglutarate	Glu, Gln, Arg, His, Pro	Glucogenic
Succinyl-CoA	Ile, Met, Thr, Val	Glucogenic
Fumarate	Phe, Tyr (Asp via urea cycle)	Glucogenic
Oxaloacetate	Asp, Asn	Glucogenic
Acetyl-CoA, acetoacetyl-CoA	Leu, Lys, Phe, Tyr, Trp, Ile, Thr	Ketogenic

Glucogenic amino acids give pyruvate or a TCA intermediate and so can make glucose; **ketogenic** ones give acetyl-CoA or acetoacetyl-CoA and can make ketone bodies but not glucose. **Leucine and lysine** are the only purely ketogenic amino acids; isoleucine, phenylalanine, tryptophan, tyrosine and threonine are both.

WORKED EXAMPLE

Question (6 marks). Write the reactions by which the amino group of aspartate and of alanine can each reach free NH_4^+ in the liver. Name enzymes and coenzymes, and say what happens to each carbon skeleton.

1. Alanine + α-ketoglutarate → pyruvate + glutamate (ALT, PLP). Pyruvate can make glucose by gluconeogenesis.
2. Aspartate + α-ketoglutarate → oxaloacetate + glutamate (AST, PLP). Oxaloacetate enters gluconeogenesis or the TCA cycle.
3. Each glutamate + NAD^+ + H_2O → α-ketoglutarate + NH_4^+ + NADH (glutamate dehydrogenase, mitochondrial).
4. Net for one alanine: alanine + NAD^+ + H_2O → pyruvate + NH_4^+ + NADH. α-Ketoglutarate is regenerated.

Note. In the liver, aspartate also gives its amino group directly to the urea cycle (Chapter 6.6), so some of its nitrogen bypasses GDH.

EXAM TRAPS

- Transamination does not release free ammonia; it only moves the amino group. Deamination releases it.
- The coenzyme of transamination and decarboxylation is PLP (vitamin B_6), not NAD^+.
- Leucine and lysine are purely ketogenic; "leucine and lysine" is a favourite one-mark answer.
- SGPT is ALT and SGOT is AST. Do not swap them.
- Glutamate dehydrogenase uses both NAD^+ and $NADP^+$; most dehydrogenases use one only.

CHECK YOURSELF

– REMEMBER **What is the common amino-group acceptor in transamination?** 1 mark

α-Ketoglutarate, which becomes glutamate.

– REMEMBER **Name the amine formed by decarboxylating histidine and glutamate.** 2 marks

Histamine and GABA (γ-aminobutyrate).

– UNDERSTAND **Explain the term transdeamination.** 3 marks

Coupling of transamination (amino group to α-ketoglutarate, making glutamate) with oxidative deamination of glutamate by GDH (releasing NH_4^+ and regenerating α-ketoglutarate). Together they remove the amino group of many amino acids through one enzyme.

– UNDERSTAND **Why does muscle send nitrogen to the liver as alanine or glutamine and not as NH_4^+?** 3 marks

Free ammonia is toxic, especially to the brain. Alanine and glutamine are non-toxic carriers; alanine also brings pyruvate for gluconeogenesis.

– APPLY **Which keto acids are formed by transamination of alanine, aspartate and glutamate?** 3 marks

Pyruvate, oxaloacetate and α-ketoglutarate.

– ANALYZE **A patient's report shows ALT 400 U/L and AST 300 U/L (both far above normal). Which organ is most likely damaged, and why?** 4 marks

The liver. Both enzymes are released by damaged cells, and ALT is mainly a liver enzyme; ALT higher than AST is the typical pattern of acute liver-cell injury, as in viral hepatitis. Heart or muscle injury raises AST more than ALT.

BEYOND THE SYLLABUS

Aminotransferases are used industrially to make chiral amines for medicines; an engineered transaminase replaced a metal catalyst in the commercial synthesis of the diabetes drug sitagliptin. Amino acid oxidases are used in biosensors. The pattern of serum enzymes is a basic tool of clinical biochemistry, the subject of an elective in many biotechnology programmes. Search "biocatalytic transamination sitagliptin". Not for the exam.

6.6 Urea cycle

The urea cycle is how the liver turns toxic ammonia into **urea**, a neutral, highly water-soluble molecule that the kidneys excrete. Each urea carries two nitrogen atoms: one from free NH_4^+ and one from aspartate. Hans Krebs and Kurt Henseleit described it in 1932, the first metabolic cycle discovered. Humans and other land mammals are **ureotelic** (they excrete nitrogen mainly as urea); most bony fish are **ammonotelic** and birds and reptiles are **uricotelic** (uric acid).

You need: 6.5 Transamination and deamination, which delivers the NH_4^+ and the aspartate.

The five reactions

The cycle runs in two compartments of the liver cell: the first two steps in the mitochondrial matrix, the last three in the cytosol.

1. **Carbamoyl phosphate synthetase I (CPS-I)**, mitochondria: $NH_4^+ + HCO_3^- + 2$ ATP → carbamoyl phosphate + 2 ADP + Pi. This is the committed, rate-limiting step. CPS-I is absolutely dependent on its allosteric activator **N-acetylglutamate (NAG)**.
2. **Ornithine transcarbamoylase (OTC)**, mitochondria: carbamoyl phosphate + ornithine → **citrulline** + Pi. Citrulline leaves the mitochondrion in exchange for ornithine.

3. **Argininosuccinate synthetase**, cytosol: citrulline + **aspartate** + ATP → argininosuccinate + AMP + PPi. The second nitrogen enters here. Splitting ATP to AMP costs two high-energy bonds.
4. **Argininosuccinate lyase**, cytosol: argininosuccinate → **arginine** + **fumarate**.
5. **Arginase**, cytosol: arginine + H_2O → **urea** + ornithine. Ornithine goes back into the mitochondrion to start the next turn. Arginase is found in large amounts only in the liver, which is why only the liver makes much urea.

Overall:

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NH4+ + HCO3− + aspartate + 3 ATP + H2O
      → urea + fumarate + 2 ADP + 2 Pi + AMP + PPi
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Three ATP are used, but four high-energy phosphate bonds are spent (two at CPS-I, two at argininosuccinate synthetase because PPi is hydrolysed).

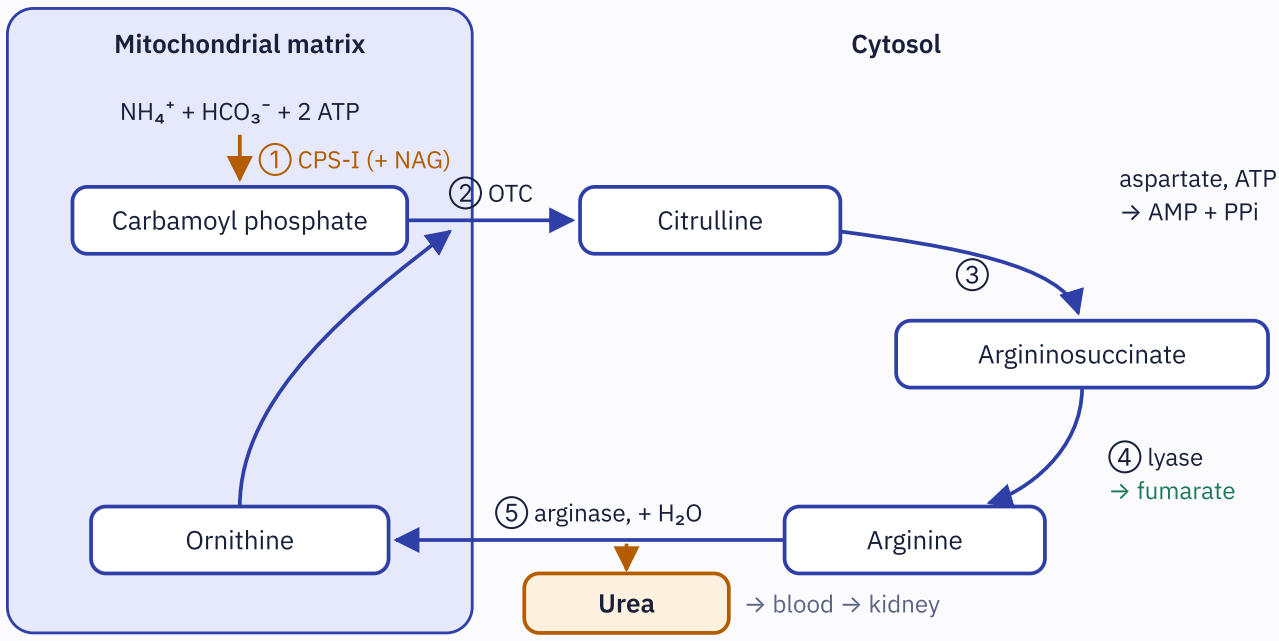


Figure 6.6.1 The urea cycle. Steps ① and ② are in the mitochondrion, ③ to ⑤ in the cytosol. One nitrogen enters as NH_4^+ at ①, the other from aspartate at ③; ornithine is regenerated and the carbon of aspartate leaves as fumarate.

Links to the TCA cycle and regulation

The fumarate made at step ④ is hydrated to malate and oxidised to oxaloacetate in the cytosol (giving NADH); oxaloacetate is transaminated back to aspartate, which feeds step ③ again. This link between the two cycles is called the **aspartate–argininosuccinate shunt** or the "Krebs

bicycle". The NADH it produces (worth about 2.5 ATP in the electron transport chain) pays back part of the cycle's cost.

Regulation works on two time scales:

- **Short term:** NAG activates CPS-I. NAG is made from acetyl-CoA and glutamate by NAG synthase, which arginine activates. When amino acid breakdown rises, glutamate and arginine rise, NAG rises and the cycle speeds up.
- **Long term:** a high-protein diet or starvation (when muscle protein is used for fuel) increases the amounts of all five enzymes.

Hyperammonaemia and urea cycle disorders

If the liver fails (cirrhosis, severe hepatitis) or a urea cycle enzyme is missing, blood ammonia rises. Ammonia is especially toxic to the brain: one proposed reason is that converting excess ammonia to glutamine drains α-ketoglutarate and glutamate from brain cells and makes astrocytes swell. Symptoms are vomiting, lethargy, tremor, slurred speech and, at high levels, coma.

A deficiency of each of the cycle enzymes is known. **OTC deficiency** is the most common and is X-linked; the others are autosomal recessive. In OTC deficiency, carbamoyl phosphate leaks into the cytosol and is used for pyrimidine synthesis, so **orotic acid** appears in urine (see Chapter 6.7). Treatment is a low-protein diet with essential amino acids, and drugs such as sodium benzoate and sodium phenylbutyrate, which combine with glycine and glutamine respectively and carry nitrogen out in urine, bypassing the cycle.

WORKED EXAMPLE

Question (6 marks). An adult excretes 30 g of urea in 24 hours. Calculate (a) the nitrogen excreted as urea and (b) the amount of protein this nitrogen represents. Urea is $CO(NH_2)_2$, molar mass 60 g/mol; protein is about 16% nitrogen.

1. Each urea has 2 N atoms: 2 × 14 = 28 g N per 60 g urea.
2. (a) Nitrogen = 30 × 28/60 = **14 g N per day**.
3. Protein is 16% N, so 1 g N comes from 100/16 = 6.25 g protein.
4. (b) Protein = 14 × 6.25 = **87.5 g protein per day**.
5. Check: an adult eating about 85–90 g protein a day and in nitrogen balance would excrete about this much urea N (urea is the major, but not the only, nitrogenous waste; the rest is ammonium, creatinine and uric acid).

EXAM TRAPS

- CPS-I (mitochondrial, uses NH_4^+, needs NAG, urea cycle) is not CPS-II (cytosolic, uses glutamine, no NAG, pyrimidine synthesis).
- Urea's two nitrogens come from NH_4^+ and aspartate. Its carbon comes from HCO_3^- (CO_2), not from ornithine.
- Three ATP are used but four high-energy bonds are spent.
- Ornithine and citrulline are amino acids that are not in proteins; arginine is made in the cycle but is semi-essential in children.
- Fumarate links the urea cycle to the TCA cycle; draw the link if the question says "relationship between".

CHECK YOURSELF

– REMEMBER **Name the two urea cycle enzymes in the mitochondrion.** 2 marks

Carbamoyl phosphate synthetase I and ornithine transcarbamoylase.

– REMEMBER **What is the allosteric activator of CPS-I?** 1 mark

N-acetylglutamate.

– UNDERSTAND **Explain the "Krebs bicycle".** 4 marks

Fumarate from argininosuccinate lyase becomes malate and oxaloacetate (giving NADH), and oxaloacetate is transaminated to aspartate, which re-enters the urea cycle. The two cycles are thus joined through fumarate and aspartate.

– UNDERSTAND **Why does orotic acid appear in urine in OTC deficiency?** 3 marks

Carbamoyl phosphate cannot be used to make citrulline, builds up, leaves the mitochondrion and enters the cytosolic pyrimidine pathway, producing excess orotate.

– APPLY **How many grams of nitrogen are in 45 g of urea?** 2 marks

45 × 28/60 = **21 g N**.

– ANALYZE **Why does a person on a very high-protein diet show higher urea cycle enzyme levels than a person on a normal diet?** 4 marks

Extra amino acids are not stored, so more are deaminated and more NH_4^+ must be disposed of. Rising glutamate and arginine raise NAG within hours; over days, the liver makes more of all five enzymes to match the higher nitrogen load.

BEYOND THE SYLLABUS

Urea cycle disorders are now treated with newer nitrogen scavengers (glycerol phenylbutyrate), liver transplantation, and in trials with gene therapy delivering the OTC gene to liver cells. Blood urea nitrogen (BUN) and creatinine are routine kidney function markers. Engineered probiotic bacteria that consume ammonia in the gut have been tested for hyperammonaemia. Search "urea cycle disorder gene therapy". Not for the exam.

Key terms of this lesson

TERM	MEANING OR FORMULA	CHAPTER
HMG-CoA reductase	HMG-CoA → mevalonate (2 NADPH); rate-limiting for cholesterol; statin target	6.4
Transamination	Amino acid + α-ketoglutarate ⇌ keto acid + glutamate (PLP)	6.5
Glutamate dehydrogenase	Glutamate → α-ketoglutarate + NH_4^+ (NAD^+ or $NADP^+$)	6.5
Urea cycle	NH_4^+ + HCO_3^- + aspartate + 3 ATP → urea + fumarate; 4 high-energy bonds	6.6
Urea nitrogen	g N = g urea × 28/60; protein ≈ g N × 6.25	6.6

Glossary (terms used in this lesson)

Aminotransferase PLP enzyme that moves an amino group from an amino acid to a keto acid.

AMPK AMP-activated protein kinase; energy sensor that stops synthesis and starts fuel oxidation.

Carbamoyl phosphate synthetase CPS-I (mitochondria, NH_4^+, urea cycle) or CPS-II (cytosol, glutamine, pyrimidines).

Glutamate dehydrogenase Enzyme that releases NH_4^+ from glutamate, using NAD^+ or $NADP^+$.

HMG-CoA	β-Hydroxy-β-methylglutaryl-CoA; intermediate of both ketogenesis and cholesterol synthesis.
Ketogenic amino acid	One whose skeleton gives acetyl-CoA or acetoacetyl-CoA; leucine and lysine are purely ketogenic.
Ketone bodies	Acetoacetate, β-hydroxybutyrate and acetone.
N-acetylglutamate	Obligate activator of carbamoyl phosphate synthetase I.
Phosphatidic acid	Diacylglycerol 3-phosphate; precursor of TAG and glycerophospholipids.
PLP	Pyridoxal phosphate, the vitamin B_6 coenzyme of transamination and decarboxylation.
Transdeamination	Transamination to glutamate followed by oxidative deamination of glutamate.
Urea cycle	Liver pathway that converts NH_4^+ and aspartate nitrogen into urea.
Uric acid	End product of purine breakdown in humans; its crystals cause gout.

The full unit book

Every chapter of Unit 6, the unit summary, the exam question bank with model answers and the full glossary: Biochemistry · Unit 6 · Lipid, Amino Acid and Nucleotide Metabolism (one file, works offline).

Sources and further reading

- D. L. Nelson and M. M. Cox, *Lehninger Principles of Biochemistry*, W. H. Freeman: chapters on fatty acid catabolism, amino acid oxidation and urea production, lipid biosynthesis, nucleotide biosynthesis and hormonal regulation (from memory; check chapter numbers in your edition).
- J. M. Berg, J. L. Tymoczko, G. J. Gatto and L. Stryer, *Biochemistry*, W. H. Freeman (from memory; check).
- D. Voet and J. G. Voet, *Biochemistry*, Wiley (from memory; check).
- U. Satyanarayana and U. Chakrapani, *Biochemistry*, Elsevier India; widely prescribed in Indian universities, uses the older P/O values of 3 and 2 in ATP calculations (from memory; check).
- V. W. Rodwell and others, *Harper's Illustrated Biochemistry*, McGraw-Hill; clinical correlations and inborn errors (from memory; check).

- StatPearls, Physiology, Urea Cycle, NCBI Bookshelf (opened; confirms N-acetylglutamate as the obligate activator of CPS-I and OTC deficiency as the most common, X-linked urea cycle defect).
- StatPearls, Biochemistry, Ketogenesis, NCBI Bookshelf (opened; confirms that the liver lacks thiophorase and that urine dipsticks mainly measure acetoacetate).

Syllabus: the University free n easy universal syllabus, built from top universities' syllabi.

Built for the University free n easy YouTube channel from the universal syllabus of Biochemistry (Oct 2026). Written with top universities' syllabi and standard textbooks; check a formula against your prescribed book before an exam, and report mistakes on the channel.