

## Supplementary material

### **Keeping cool and staying warm: a tale of testes and uteruses in marine mammals**

#### **Testicular thermoregulation**

Spermatogenesis requires temperatures several degrees below core body temperature. In terrestrial mammals, this is achieved via a scrotum; however, most marine mammals lack an external scrotum, necessitating alternative adaptations.

#### ***Cetaceans (Whales, dolphins)***

- Testes are intraabdominal, located near the body core.
- Cooling is achieved via a countercurrent heat exchange system, primarily:
  - A pampiniform plexus-like venous network surrounding the testicular artery.
  - Cooled venous blood returning from peripheral regions (e.g. dorsal fin, flukes) absorbs heat from incoming arterial blood.
- Arterial blood is pre-cooled before reaching the testes.
- Additional cooling comes from high surface area vascular beds in appendages exposed to cold seawater.

Key feature: Internalized testes + vascular countercurrent heat exchange

#### ***Phocids (True seals)***

- Testes are also internal, often located in a more posterior abdominal or inguinal position.
- Cooling relies heavily on:
  - A well-developed venous plexus associated with the testes.
  - Direct conductive cooling when hauled out on ice or land.
- Compared to cetaceans, seals may rely slightly more on environmental conductive heat loss, especially during terrestrial phases.

Key feature: Combination of vascular exchange + environmental cooling

#### **Uterine thermoregulation**

- The uterus does not require temperatures as low as testes, but thermal stability is critical for:
  - Early embryonic development
  - Implantation success
- Marine mammals often experience delayed implantation (embryonic diapause), adding another layer of physiological control.

#### **Across marine mammals**

- The uterus is deep within the body cavity, benefiting from core thermal stability.
- Unlike testes, there is no strong need for active cooling below core temperature.

- Instead, thermoregulation focuses on:
  - Avoiding thermal fluctuations
  - Maintaining a stable, slightly cooler microenvironment during early pregnancy

### Vascular adaptations

- Some species exhibit uterine vascular countercurrent systems, though less specialized than in testes.
- Blood flow regulation may help:
  - Buffer temperature changes
  - Support embryo survival during diapause

### Functional contrast with testes

- Testes: Active cooling required
- Uterus: Thermal stability required, not active cooling

### Key differences: thermoregulation of testis versus uterus

| Feature                 | Testis                                          | Uterus                                                 |
|-------------------------|-------------------------------------------------|--------------------------------------------------------|
| Thermal requirement     | Below core temperature                          | Near core temperature (stable)                         |
| Location                | Internal (no scrotum)                           | Deep abdominal                                         |
| Mechanism               | Countercurrent heat exchange (highly developed) | Mild vascular regulation                               |
| Sensitivity             | High (spermatogenesis temperature-dependent)    | Moderate (embryonic development sensitive to extremes) |
| Environmental influence | Indirect (via vascular cooling)                 | Minimal direct influence                               |
| Special adaptations     | Pampiniform plexus analogs                      | Support for diapause and implantation timing           |

### Conceptual takeaway

- **Male system (testis):** engineered for heat dissipation in a cold but insulating aquatic environment.
- **Female system (uterus):** optimized for thermal buffering and stability, supporting long gestation and delayed implantation.

### Integration with marine adaptation

Both systems are tightly linked to broader marine mammal physiology:

- Blubber insulation conserves heat but creates a challenge for testicular cooling.
- Peripheral vascular adaptations (fins, flukes) act as heat exchangers, supporting reproductive thermoregulation.

- Reproductive timing strategies (e.g. diapause) reduce dependence on strict thermal windows.