1

The Decay of Human Bodies

OBJECTIVES

Compare the chemical and physical characteristics of the different stages of decomposition.
Explain how a body's rate of decomposition is affected by the way in which death occurred and the environment in which it is placed.
Compare the conditions that promote the formation of adipocere and of mummification and how these processes preserve body tissues.

1.1 Introduction

The time before a person dies is the *ante-mortem* period, whilst that after death is the *post-mortem* period. The moment of death is the 'agonal period' – the word being derived from 'agony', because it used to be believed that death was always a painful experience. Either side of the moment of death is the *peri-mortem* period, although there is no consensus about how many hours this should encompass. It is important to know in which of these time periods events took place in order to determine their sequence, the cause of death, and whether or not a crime might have been committed. Similarly, it is important to know the length of the post-mortem period, referred to as the *post-mortem* interval (PMI). This is because by knowing exactly when death occurred it is possible, among other things, to either include or exclude the involvement of a suspect. The study of what happens to remains after death is 'taphonomy' and the factors that affect the remains are 'taphonomic processes'. Thus, burning, maggot feeding, and cannibalism are all examples of taphonomic processes.

When investigating any death, it is essential to keep an open mind as to the possible causes. For example, if the partially clothed body of a woman is found on an isolated moor, there are many possible explanations other than she was murdered following a sexual assault. First, she may have lost some of her clothes after death, through them decaying and blowing away or from them being ripped off by scavengers. Second, she may have been a keen rambler who liked the open countryside. Most people die of natural causes and she may have suffered from a medical condition that predisposed her to a heart attack, stroke, or similar potentially fatal condition whilst out on one of her walks. Another possibility is that she may have committed suicide: people with suicidal intent will sometimes choose an isolated spot in which to die. Another explanation for the woman's death would be that she had suffered an accident, such as tripping over a stone, landing badly, and receiving a fatal blow to her head. And, finally, it is possible that she was murdered. All of these scenarios must be considered in the light of the evidence provided by the scene and the body.

Essential Forensic Biology, Third Edition. Alan Gunn.

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1.2 The Stages of Decomposition

After we die, our body undergoes dramatic changes in its chemical and physical composition and these provide an indication of the PMI. The changes also influence the body's attractiveness to detritivores (organisms that consume dead organic matter) and their species composition and abundance. These also act as indicators of the PMI. Furthermore, the post-mortem events may preserve or destroy forensic evidence, as well as bring about the formation of artefacts. For example, the discharge of bloody fluids from the mouth and nose or the bluish discoloration of the skin, which are perfectly normal consequences of decay, can be mistaken for signs of assault or poisoning. An understanding of the decay process, and factors that influence it, is therefore essential for the interpretation of dead human and animal remains.

Animal decomposition in terrestrial environments can be divided into four stages: fresh, bloat, putrefaction, and putrid dry remains. However, these stages merge into one another and it is impossible to separate them into discrete entities. Indeed, bloat results from the process of putrefaction and therefore is dealt with as a sub-section of putrefaction in this chapter. In addition, a body seldom decays in a uniform manner. Consequently, part of the body may be skeletonised, whilst another part retains fleshy tissue.

1.2.1 Fresh

Once the heart stops beating, the blood pressure drops and blood is no longer moved through the body. The blood within the vessels therefore settles under gravity to the lowermost dependent regions. Consequently, shortly after death, the skin and mucous membranes appear pale. Once the circulation ceases, tissues and cells no longer receive oxygen and nutrients and they begin to die. Different cells die at different rates, so, for example, brain cells die within 3–7 minutes, while skin cells can be taken from a dead body for up to 24 hours after death and still grow in a laboratory culture. Contrary to folklore, human hair and fingernails do not grow after death, although shrinkage of the surrounding skin makes it seem as though they do.

1.2.1.1 Temperature Changes

Because normal metabolism ceases after death, our body starts to cool in a process known as *algor mortis*: literally, the coldness of death. For many years, measurements of body temperature were the principal means of determining the PMI. However, the technique suffers from a variety of shortcomings. To begin with, the skin surface usually cools rapidly after death and the mouth often remains open. Therefore, measurements recorded from the mouth or under the armpits would not reflect the core body temperature. In living persons, one way of determining core body temperature is with a rectal thermometer. However, this approach is not always appropriate in forensic cases. This is because inserting a rectal thermometer often requires moving the body and removing the clothing. This potentially interferes with evidence collection in cases where anal intercourse before or after death occurred.

Nowadays, the body temperature of living humans and many domestic animals is often determined from the temperature in the external auditory canal, measured using a custom-designed electronic digital ear thermometer. This has the advantage of being quick, non-invasive, and does not risk cross contamination or breakage of the thermometer in the body. The external auditory canal temperature correlates well with the brain temperature and it is useful for recording the temperature of dead bodies in hospital settings (Baccino *et al.* 1996). Unfortunately, in forensic scenarios, there are often complications that make the measurement of the ear temperature either difficult or the interpretation of the results questionable (Rutty 1997); for example, if the body is submerged or water enters the ear canal

Table 1.1 Factors affecting the rate at which a body cools after death.

Factors that enhance the rate of cooling
Small body size
Low fat content
Body stretched out
Body dismembered
Serious blood loss
Lack of clothes
Wet clothes
Strong air currents
Low ambient temperature
Rain, hail
Cold, damp substrate that conducts heat readily (e.g. damp clay soil)
Body in cold water
Dry atmosphere
Factors that delay the rate of cooling
Large body size
High fat content
Foetal position (reduces the exposed surface area)
Clothing – the nature of clothing is important because a thin, highly insulated layer can provide more protection than a thick poorly insulated material.
Insulated covering (e.g. blanket, dustbin bags, paper, etc.)
Protection from draughts
Warm ambient temperature
Warm microclimate (e.g. body next to a hot radiator)
Exposed to the sun
Insulated substrate (e.g. mattress)
High humidity

from rain or condensation, if there is bleeding into the ear canal following a skull fracture, and if there is traumatic damage to the ears from blows to the head.

A second major problem with using body temperature as a measure of the PMI is that the rate of cooling depends upon a host of complicating factors. These start with the assumption that the body temperature at the time of death was 37 °C. In reality the body temperature may be higher (e.g. owing to infection, exercise, or heat stroke) or lower (e.g. hypothermia or severe blood loss). In addition, the rate of temperature loss depends upon numerous factors (Table 1.1). For example, subcutaneous fat acts as an insulator that reduces the rate at which heat is lost from the body. Adult women tend to have a higher fat content than men, and therefore the bodies of a woman and a man of the same weight cool down at different rates. Similarly, the body of a fat man who dies inside a car on a hot sunny day may not lose heat to any appreciable extent; indeed, his body temperature may even increase.

Various formulae relate body temperature to the length of time since death, but these are mostly too simplistic to be reliable. Clauss Henßge designed a sophisticated nomogram that accounts for body weight and environmental temperature and allows application of corrective factors according to the individual circumstances of the case (Henssge and Madea 2004). A nomogram is a graphical calculator that usually has three scales (Figure 1.1). Two of these scales record known values (rectal and environmental temperature) and the third scale is the one from which the result is read off (time since death). Unfortunately, even this approach has limitations – for example, it is not reliable if the body was left exposed to the sun or if there is reason to believe that it was moved after death. In the latter situation, the body experiences

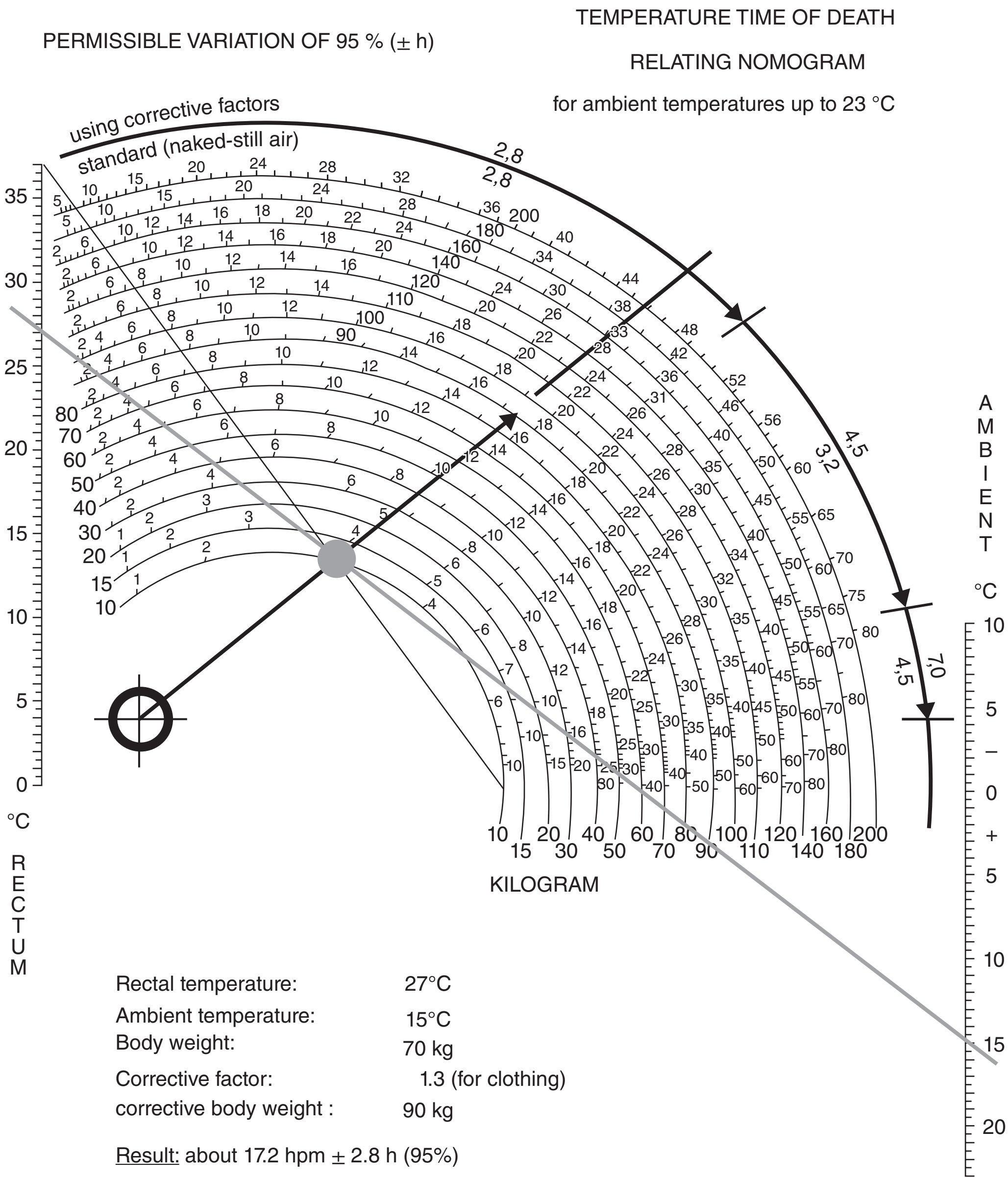


Figure 1.1 Clauss Henßge's nomogram for the determination of time since death from body temperature. *Source:* Reproduced from Henssge and Madea (2004), © Elsevier, with permission. The nomogram works as follows: (a) One draws a straight line between the rectal temperature and the ambient temperature. In this case, one draws a line from 27–15 °C. (b) The 'standard' is a naked body lying in an extended position in still air and therefore 'corrective factors' are applied for any situations other than this. Henssge and Madea (2004) list these factors. In this example, the body wears three thin layers of dry clothes in still air and therefore the corrective factor is 1.3. One multiplies the weight of the body by the corrective factor. The body weighs 70 kg and therefore 70 x 1.3 = 91 kg. The nomogram goes up in units of 10 and therefore 91 kg rounds down to 90 kg. (c) One draws a second straight line from the centre of the circle that is found at the left-hand side of the nomogram, so that it hits the intersection of the nomogram's diagonal line and that drawn between the rectal temperature and the ambient temperature in step (a). The line then continues until it hits the outermost circle. (d) Where the line drawn in step (c) hits the 90 kg semi-circle is the time since death (17.2 hours). Where the line hits the outermost circle, one can read off the 95% confidence limits (2.8 hours). Therefore, the person was dead for 17.2 ± 2.8 hours (95% CI).

at least two different environments and therefore spends time cooling at two or more rates. This is not to say that temperature measurements are of limited value, but one should be aware of possible complicating factors.

Body temperature, like most biological measurements of the PMI, is a 'rate method'. Rate methods initiate or cease at the time of death and the subsequent rate of change provides an estimate of elapsed time. Other examples include the increase in the potassium ion concentration in the vitreous humour of the eye, the development of *rigor mortis* and the growth of maggots on the dead body. Rate methods become increasingly inaccurate the longer the PMI, because they are influenced by a wide variety of biotic and abiotic factors. However, as long as their limitations are recognised, they can be extremely useful and concordance between several different methods means the time of death is predictable with a fair degree of confidence. Furthermore, in the absence of any other evidence, an indication is more useful to a police investigation than nothing at all. The other methods of determining the time since death are 'concurrence methods'. They work by evaluating the occurrence of events that happened at known times at or around the time of death. Typical concurrence events are finding that the victim's watch stopped at a particular time as a consequence of being smashed (e.g. following a fall or during a struggle) or that mobile phone records indicate that a victim was alive until at least a certain date and time.

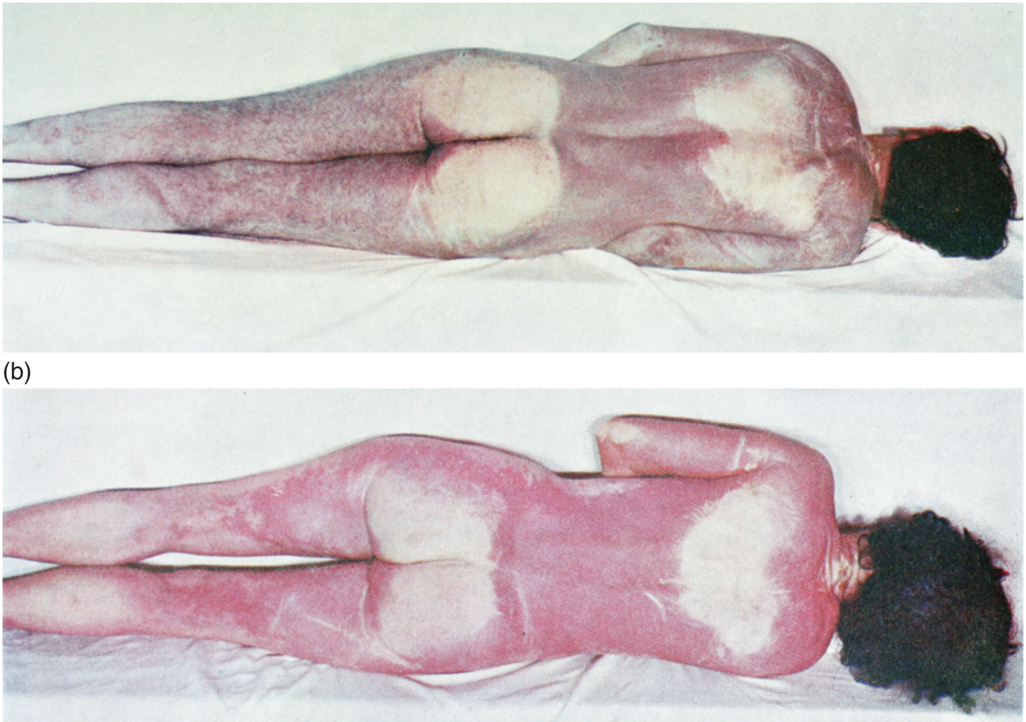
1.2.1.2 Chemical Changes

Owing to the lack of oxygen, after death cellular processes switch from aerobic to anaerobic, and there are dramatic increases and decreases in specific metabolites. Furthermore, as membrane integrity is lost, metabolites redistribute within and between tissues. These changes do not take place uniformly throughout the body at the same time. For example, energy metabolism ceases more rapidly in the blood than the vitreous humour of the eye. Unfortunately, few studies compare changes in different chemicals or compare chemical changes with other existing techniques for determining the PMI. In addition, most studies to date lack field data. More work is also needed on the influence of taphonomic factors, such as temperature, and ante-mortem factors, such as age, drug use and disease, on post-mortem chemical changes. The most commonly used chemical measurement of PMI is the determination of potassium ion concentration in the vitreous humour of the eye. However, there are marked discrepancies between authors concerning its reliability.

1.2.1.3 Hypostasis

Between 20 and 120 minutes after death, hypostasis (also called *livor mortis* and post-mortem lividity) occurs – it develops in all bodies, but may be difficult to observe. Hypostasis is a purple or reddish purple discoloration of the skin caused by the blood settling in the veins and capillaries of the dependent parts of the body (Figure 1.2a). Blood plasma also settles to the dependent regions and this causes oedema (fluid accumulation) and the formation of blisters on the surface of the skin. If the person is lying on their back, hypostasis will develop in the back and those body surfaces adjacent to the ground, whilst if the person is hanging by their neck, pronounced hypostasis will develop in their hands, forearms, and lower legs. It starts as a series of blotches that then spread and deepen in colour with time. Initially, blood remains in the blood vessels, but eventually the red blood cells haemolyse (break down and rupture) and the pigment diffuses out into the surrounding tissues. Here it becomes metabolised to sulphaemaglobin that gives rise to a greenish discoloration. Sulphaemoglobin is not present in normal blood, although it may be formed after exposure to drugs such as sulphonamides. This emphasises that normal decomposition processes may mimic those induced before death or by the action causing death.

(a)



(b)

Figure 1.2 Characteristic pattern of hypostasis and pressure pallor resulting from a dead body lying on its back. In (a), the person died of natural causes, whilst in (b) the person died of carbon monoxide poisoning – note the brighter coloration of the hypostasis. The reddening results from the settling of blood in the veins, whilst the pale regions are where the pressure of the body against the underlying substrate has constricted the vessels. *Source*: Reproduced from Kerr (1957).

The rate of development of hypostasis varies from body to body and is also influenced by underlying medical conditions, such as circulatory disease. Consequently, there is variation in the literature about when events begin and when they reach their maximal effect. Indeed, hypostasis may not develop at all in infants, the elderly or those suffering from anaemia. Some of the literature suggests that after about 10–12 hours of a body remaining in a set position, the discoloration caused by hypostasis becomes 'fixed'. Furthermore, if the body is then moved and left in a different position, a second area of discoloration forms. Two or more distinct patterns of discoloration therefore indicate movement of the body. However, according to Saukko and Knight (2015), there is so much variation in the time it takes for 'fixation' to develop, if it develops at all, that it is not a reliable forensic indicator of the PMI or evidence of movement after death.

Pressure, whether from tight fitting clothes such as belts and bra straps, a ligature around the neck, ropes used to bind hands together, or corrugations in the surface on which the body is resting, prevent underlying blood vessels from filling with blood. Therefore, these regions appear paler than their surroundings – this is 'pressure pallor' or 'contact pallor'. Whilst the body is fresh, *ante mortem* bruising and hypostasis are distinguishable, because bruising results from the leakage of blood out of damaged blood vessels into the surrounding tissues and the consequent formation of clots. By contrast, in hypostasis, the blood is restricted to dilated blood vessels. However, as time passes and tissues decay, blood begins to leak out of the vessels and it becomes more difficult to distinguish between the two.

Initially, blood remains liquid within the circulatory system after death, rather than coagulating, because of fibrinolysins released from the capillary walls. These destroy fibrinogen and therefore prevent clots from forming. However, wounds inflicted after death do not bleed profusely, because the heart is no longer beating and therefore blood pressure is zero. Therefore, blood from even a severed artery trickles out because of gravity, rather than spurting out as it would during life. A common question on finding a body that had fallen several metres at the base of a building is whether the victim was alive before hitting the floor. This is important because a murderer may attempt to mask wounds caused by an assault within the much greater trauma caused by a fall from a great height. That is, the crime would be mistaken for an accident or suicide. A dead body would bleed less on impact than a live body. Furthermore, a bleeding body would leave stains at the point 'take-off' and cast off stains during the fall.

Unlike the situation on land, a dead body floating on water may suffer considerable loss of blood from wounds. After initially sinking, a dead body rises to the surface owing to the accumulation of gas from the decay process and then floats face downwards. Consequently, the blood pools in the facial and dependent regions and wounds affecting these areas bleed profusely. Bodies floating in the sea frequently suffer extensive post-mortem wounds from dashing against rocks, boats, and other maritime structures. Boat propellers cause serious lacerations to floating bodies and potential dismemberment, whilst seagulls cause stab-like wounds.

1.2.1.4 Changes in Muscle Tone

Immediately after death, muscles usually become flaccid, and the joints relax such that a person's height may increase by as much as 3 cm. Furthermore, the body may be found in a posture that would be highly uncomfortable in life. Once consciousness is lost, a standing individual collapses without attempting to break their fall, whilst a seated individual slumps forwards (usually) and may fall to the floor unless supported. Consequently, the body may receive injuries which might themselves have been life-threatening had the person not already been dead. The relaxation of muscles can lead to the sphincters loosening, and the release of urine and faeces or the regurgitation of gut contents at or shortly after the moment of death. Suffocation can lead to the victim urinating involuntarily, but this may also happen naturally at the time of death. Therefore, it would be unwise to make too much of such findings, unless there was other evidence to indicate that criminal activity was involved. By contrast, when a person is in a coma, the volume of urine in the bladder can increase markedly, because they are not responsive to stimuli that would normally wake them up. Consequently, an unusually distended bladder is an indication that a person was comatose for several hours before they died.

1.2.1.4.1 Rigor Mortis

About 20 minutes after death, *rigor mortis*, the stiffening of muscles and limbs, manifests itself in the eyelids and small muscles of the face. The stiffening then spreads to the other muscle groups over the subsequent hours. There is some discrepancy in the literature about how long it takes for the whole body to become rigid, with various figures of between 2 and 12 hours being quoted. This is because the speed of development of rigor mortis and its duration are both heavily influenced by environmental temperature, with onset commencing earlier and duration shorter at high environmental temperatures. By contrast, onset is delayed at low temperatures and at a constant 4 °C may last for at least 16 days, with partial stiffening still detectable up until 28 days after death (Varetto and Curto 2005). Children tend to develop rigor mortis sooner than adults, whilst onset is delayed if death was owing to asphyxiation or to poisoning with carbon monoxide. The extent and degree of rigor mortis is therefore not an especially accurate measure of the PMI.

Rigor mortis is breakable by pulling forcefully on the affected limbs but, depending upon the time since death, may subsequently re-set. This provides a crude estimate of the time since death. A common assumption is that rigor will re-establish if the person was dead for less than eight hours. However, Anders *et al*. (2013) show that this figure is a considerable underestimate and that while the percentage of instances in which rigor mortis re-establishes declines with time, it can still happen up to 19 hours after death.

Rigor mortis affects both the skeletal and the smooth muscles. When it affects the *arrector pili* muscles, it results in 'goose bumps' and the scalp and body hairs standing on end. This can make it look as though a person died in a state of shock. The *arrector pili* are smooth muscles running from the superficial dermis of the skin to the side of the hair follicles. Normally, our hair emerges at an angle to the skin surface, but when the *arrector pili* are stimulated to contract – for example, as a consequence of the body's response to cold or stress – the hair is pulled into a more upright position. This also gives rise to the phenomenon of 'goose bumps'.

Rigor mortis results from the rise in the intracellular concentration of calcium ions in muscle cells following death. This happens because the membranes around the sarcoplasmic reticulum and the cell surface become leaky. Consequently, calcium ions move down their concentration gradient into the cytoplasm of the muscle cells. This rise causes the regulatory proteins troponin and tropomyosin to move aside, thereby permitting the muscle filaments actin and myosin to form cross bridges. This is possible because the heads of myosin molecules already contain adenosine triphosphate (ATP). However, actin and myosin, once bound, cannot detach from one another, because this process requires ATP – and this is no longer being formed. Thus, the actin and myosin filaments remain linked together by immobilised cross bridges, resulting in the stiffened condition of dead muscles.

Rigor mortis gradually subsides and disappears entirely after about 36 hours, although this happens sooner in warm conditions. The muscles then become extremely flaccid, because the cross bridges between the muscle fibres are broken and the muscle proteins are decaying. Consequently, the anal sphincter and muscles surrounding the anal canal become loose and therefore the anus spreads open. This condition is referred to as 'patulous' and can give rise to a suspicion that the person was subject to anal intercourse/interference. Checking for bruising and abrasions to the anal canal and the presence of sperm or foreign bodies could alleviate this suspicion. Similarly, in women, the vulva and vagina become more distensible. This should not be mistaken for evidence of sexual assault, especially in children below the age of consent.

Rigor mortis can indicate the relationship between a body and a situation. This is because once rigor mortis develops, it results in a body taking on a fixed position. Consequently, the body cannot adopt a new position until rigor is broken. For example, a body that is curled to fit into the boot of a car or large suitcase will keep this position after removal. Its position can therefore provide an indication as to whether a particular car or suitcase might have been the means of transport. Similarly, a body found with one or more limbs raised without an obvious means of support suggests that rigor set in whilst the body was in a different position that supported the limb(s). The relaxation of muscles that accompanies death means that a standing person almost always slumps to the floor. However, Pirch *et al*. (2013) describe an unusual case in which the body of a dead woman was found in a standing position. The situation arose because at the time of death she was leaning against supports that kept her body upright whilst rigor mortis set in.

Exposure to sub-zero temperatures causes the body to stiffen but prevents the onset of rigor mortis entirely. In this case, the body becomes flaccid when it warms up and then subsequently exhibits rigor mortis. In this way, a murderer may confuse a police investigation by storing his victim in a freezer immediately after death before disposing of it later. One of the best-known examples of this is the case of the mafia hitman, Richard Kurlinski (1935–2006). He earnt the sobriquet 'the iceman', because he would sometimes store his victims in a commercial deep freeze and dispose of the bodies months or even years later. His *modus operandi* was discovered when he didn't let one of his victims defrost thoroughly and the body was discovered on a warm summer's night with a partially frozen heart (Zugibe and Costello 1993).

There is a considerable literature in the food science sector on means of distinguishing between fresh and frozen meat. However, there are far fewer studies on human tissues. Miras *et al*. (2001) suggest that it is possible to identify previously frozen muscle tissue by its higher levels of the enzyme short-chain 3-hydroxyacyl-CoA dehydrogenase. It is uncertain how effective this would be in practice and would presumably rely on discovering the body within a few hours of defrosting. Freezing results in ice crystal formation, both within cells and in extracellular fluids and osmotic damage owing to changes in ion balances. Consequently, histological changes such as extended extracellular spaces and cell shrinkage are observable in histological sections (Schäfer and Kaufmann 1999).

1.2.1.4.2 Cadaveric Rigidity

So-called 'cadaveric rigidity', 'instantaneous rigor' or 'cadaveric spasm' is a contentious term. Some forensic pathologists dispute its existence, whilst others consider it a genuine phenomenon, albeit rare (Bedford and Tsokos 2013; Fierro 2013). Unlike rigor mortis, 'cadaveric rigidity' allegedly sets in immediately after death and affects part or all of the body. A common belief is that cadaveric rigidity occurs in the bodies of people who die in a state of extreme emotional and physical stress. For example, cadaveric rigidity is often given as the reason a person who shoots himself is found tightly grasping his gun, whilst a murder victim is found with tufts of his assailant's hair clenched in his hands. However, most murder victims and many who die of painful medical conditions are highly stressed at the time of death. It is also surprising that cadaveric rigidity does not appear to be documented as a feature of those who underwent judicial executions in the UK during the nineteenth and twentieth centuries. The law demanded that a doctor be present at these executions and he would subsequently undertake a post-mortem. Therefore, if extreme stress is a requirement for cadaveric rigidity, then one would expect it to be relatively common rather than a rare phenomenon.

To date, no physiological mechanism explaining how instantaneous rigor might occur is available. Most instances are probably a consequence of gravity and positioning retaining the object in a person's hand during the initial muscle relaxation phase. Afterwards, normal rigor mortis sets in and the object becomes firmly grasped again.

1.2.1.4.3 Heat Stiffening

Heat stiffening is distinct from rigor mortis and results from exposing a body to extreme heat. This causes the body to exhibit a 'pugilistic posture' and evidence of severe burning will inevitably be apparent.

1.2.1.5 Indications of Poisoning in a Fresh Body

Sometimes the cause of death results in striking changes to normal skin coloration. For example, deaths from carbon monoxide poisoning often result in a cherry red/pink coloration to the skin, lips, and internal body organs (Figure 1.2b). However, several hours after death, the coloration may not be immediately apparent, owing to the settling of the blood to the dependent regions. Carbon monoxide gas forms during the combustion of many substances and poisoning is a common feature of accidental deaths in which people are exposed to fumes from a faulty gas boiler or during fires and suicides, in which the victim breaths in vehicle exhaust fumes. Carbon monoxide poisoning may cause death in homicides resulting from arson or the deliberate blocking of the flue to a fire or gas boiler. Carbon monoxide has much greater affinity than oxygen for the haeme molecule of haemoglobin. Therefore, even at low atmospheric concentrations, it rapidly replaces oxygen and thereby reduces the oxygen carrying capacity of the blood. When carbon monoxide binds with haemoglobin in the blood or myoglobin in the muscles, it forms carboxyhaemoglobin and carboxymyoglobin respectively and they are responsible for the pink coloration. However, carbon monoxide poisoning does not always result in the formation of a cherry pink coloration (Carson and Esslinger 2001) and it can be difficult to spot when the victim is dark skinned – though it may be apparent in the lighter regions such as the palms of the hands or inside the lips or the tongue. There are big differences in susceptibility to carbon monoxide poisoning. This is partly a consequence of age, size, and general health. For example, children are more susceptible owing to their higher respiration rate.

Cyanide poisoning also causes cherry red skin coloration, although it is said to be somewhat darker than that caused by carbon monoxide. Cyanide may be ingested as a means of suicide and homicide, and it is sometimes a lethal component of smoke. Cyanide forms during the combustion of many substances (e.g. wool, plastics) and its effect in conjunction with carbon monoxide is additive, since they work by different mechanisms. Indeed, a person inhaling smoke may die of cyanide poisoning before there is a marked rise in the levels of carboxyhaemoglobin. Cyanide affects a variety of enzymes and cell processes, but has its principal effect through the inhibition of cytochrome oxidase and thereby prevents the production of ATP via oxidative phosphorylation. The cherry red coloration results from the increased oxygenation of the blood in the veins, as a consequence of the inability of cells to utilise oxygen for aerobic metabolism.

Cyanide poisoning also causes cyanosis – a bluish tinge to the skin, fingernails and mucous membranes. However, the term cyanosis derives from the blue-green colour cyan rather than the chemical cyanide. Cyanosis may be localised or widespread, and be found on its own or in conjunction with cherry red skin coloration. It results from a reduction in the level of oxygen in the blood and therefore darker deoxygenated blood imparts colour to the tissues, blood vessels, and capillaries, rather than the normal bright red oxygenated blood. Cyanosis is therefore a common symptom of a whole range of conditions that interfere with the supply of oxygenated blood to the tissues, including carbon monoxide poisoning, a heart attack, and asphyxia. Cyanide has a reputation for causing rapid, near instantaneous death. However, a lot depends on the nature of the cyanide and its means of delivery (e.g. breathing in gaseous hydrogen cyanide, ingestion of a salt in solid or liquid form, or absorption through the skin) and the dose. Death may occur within minutes of acquiring a lethal dose or take several hours. The longer the time the victim struggles to breathe the greater the probability that cyanosis will develop.

Toxicological tests are required to confirm the presence of poisons. This can be problematic if there are no clues as to what the poison(s) might be. This is because many poisons induce non-specific pathologies, but they can only be identified through specific analytical tests – and there are thousands of potentially lethal chemicals. Some poisons are difficult to detect after death and this makes it difficult to implicate them as the cause. For example, Sastre *et al.* (2013) describe an interesting case in which a mother and child died in their flat as a consequence of suspected hydrogen sulphide poisoning. Hydrogen sulphide is an extremely toxic gas that inhibits mitochondrial cytochrome enzymes and therefore cellular respiration. Its repellent smell of rotten eggs means that people usually escape from the source before they breathe in a fatal amount. However, high levels are not detectable, because they induce olfactory paralysis. In this case, the gas emanated from a blocked sink and the victims' positions indicated they lost consciousness rapidly. The woman probably caused a sudden release of large amounts of gas when she attempted to unblock the sink. Immediately after discovering the woman and child, the rescuers opened all the windows because of the awful smell.

Consequently, subsequent measurements of the air in the flat were 'normal'. The investigators were surprised that hydrogen sulphide was not detectable in the blood of either the woman or the child. Therefore, they analysed the levels of hydrogen sulphide in the lungs and these proved to be at potentially fatal concentrations. This emphasises the importance of not relying solely on blood analyses when there are grounds for suspecting a poisonous gas was inhaled. During the late1990s, there were numerous cases of people committing suicide in Japan through manufacturing hydrogen sulphide using commercially available cleaning products and recipes downloaded from websites (Morii *et al.* 2010). The 'craze' has since spread to other parts of the world. It presents risks to those who treat the victims or handle their dead bodies, if this is done in a confined space with insufficient ventilation.

The heavy metal thallium is often referred to as the 'poisoner's poison', because its salts, such as thallium sulphate, are colourless, tasteless, highly toxic and have a reputation for being difficult to detect in foods and tissues. Thallium poisoning has various non-specific consequences, depending on the dose ingested and death may not take place until weeks after ingestion. Thallium ions are similar in size to potassium ions and therefore enter via the potassium pores found on all cell membranes. Once inside the cells, the precise mechanism by which thallium exerts its effects is/are not certain, but it is known to interfere with ATP production. Although older literature states that thallium is difficult to detect, new techniques such as inductively coupled plasma mass spectrometry (ICP-MS) are more effective. Li *et al.* (2015) provide a discussion of two cases of thallium poisoning.

The use of traditional poisons, such as cyanide and arsenic, for both homicide and suicide, has declined in developed countries. This is a consequence of restrictions on the sale of products containing such harmful products to the public. Instead, many cases of poisoning are nowadays associated with the intake of narcotics and pharmaceuticals. By contrast, in developing countries and especially those in which there are many peasant farmers, poisoning with insecticides and other agrochemicals is a major cause of mortality. For example, in Bangladesh during the year 1996–1997, 14% of all reported deaths of women aged 10–50 years were due to poisoning and, whilst the numbers have since declined, they remain remarkably high (Chowdhury *et al.* 2011; Yusuf *et al.* 2000). This is because agrochemicals can be purchased easily and these often include toxic chemicals that are banned in other parts of the world.

Case Study: The Poisoning of Alexander Litvinenko with Polonium

Alexander Litvinenko died in London, UK, of polonium poisoning on 23 November 2006. He was a former KGB agent who fled Russia and became a prominent dissident. He openly criticised the Russian president, Alexander Putin, accusing him and his government of corruption. On 1 November, he had various meetings, with other ex-KGB agents and people with connections with the Russian state security, in London restaurants. One of these men allegedly spiked Litvenko's tea with polonium-210. Some hours later, Litvinenko fell seriously ill and was admitted to hospital. The cause of his illness could not be ascertained, but he accused Putin of arranging for him to be poisoned. It was initially suspected that Litvinenko was poisoned with thallium, because it had been used by the KGB in the past and it causes similar pathology to that seen in Litvinenko. However, thallium was not present in his body and the presence of polonium was not discovered until after he died. Although polonium-210 is a radionucleotide, it emits only alpha particles and this was the reason for the delay in identification. Alpha particles have high energy and damage DNA and other biomolecules, but they lack the penetrative abilities of gamma radiation. Therefore, once inside the body's tissues, they cannot be detected by Geiger counters. This also means that it is easy for polonium to be moved covertly within and between countries. Because it emits only alpha particles, it does not require heavy screening for safe transportation. In addition, radioactivity monitors at airports detect gamma radiation and therefore would not register its presence. Polonium is incredibly poisonous and weight for weight is about 2.5×10^{11} times as toxic as hydrogen cyanide (Haynes 2014). Consequently, a fatal dose is small enough to hide easily and safely among personal luggage.

Although polonium-210 has a relatively short half-life of 138.4 days, the traces of radioactivity meant that investigators could identify where Litvinenko was poisoned. Because of the manner in which Litvinenko was poisoned, others, such as restaurant workers and guests, were also exposed (e.g. from subsequently handling/drinking from the teapot and cup and from cross contamination). However, few laboratories are equipped to measure the presence of alpha particle emitting isotopes from biological samples. Consequently, screening was only offered to those who were deemed most likely to have been at risk (Maguire *et al*. 2010). Therefore, a telephone help line was set up to offer reassurance to members of the public and this received calls from 872 individuals, 7 of whom remained seriously worried because they suffered from health-related anxiety (Morgan *et al*. 2008). This emphasises that criminal acts often have consequences for the wider community, including many who have no association with the event.

Although polonium is widespread in nature and even detectable in cigarette tobacco (Radford and Hunt 1964), it is present in small amounts. Virtually all the polonium used in research and industry comes from Russian nuclear reactors – and it is extremely expensive. According to White (2008), the dose that killed Litvinenko would have cost over US$ one million. It is baffling why anyone should choose such an elaborate and expensive means of murdering someone, unless it was to demonstrate that no expense or effort would be spared. The main suspects soon moved back to Russia and to date the Russian government refuses to cooperate with the investigation into Litvinenko's death.

1.2.2 Putrefaction

Some authors distinguish several stages of putrefaction (decay), but the usefulness of this is uncertain. As the body enters the bloat stage, it is said to be 'actively decaying'. During this time, the soft body parts disappear through the actions of autolysis and microbial, insect, and other animal activity. The body then collapses in on itself as gasses are no longer retained by the skin. At this point, the body enters 'advanced decay' and, unless the body is mummified, much of the skin is lost.

Obese people tend to decay faster than those of average weight. According to Campobasso *et al*. (2001), this is due to the 'greater amount of liquid in the tissues whose succulence favours the development and dissemination of bacteria'. At first sight, this is surprising, since fat has a lower water content than most other body tissues and obese individuals therefore have a lower than average water content. However, fat acts as a 'waterproofing' agent, preventing the evaporation of water and therefore the drying out of the corpse, whilst its metabolism yields large amounts of water. Fat is also an insulator and this reduces the rate at which the body cools down after death. Consequently, decomposition and bacterial growth proceeds faster in a person with a high fat content.

1.2.2.1 Bloat

Our intestines are packed with bacteria and other microbes and they do not die with us. After death, these microbes break down the dead cells of the intestines, while some, especially the *Clostridia* and the enterobacteria, start to invade the other body parts. At the same time, the body undergoes its own intrinsic breakdown, known as autolysis. This results from the release of enzymes from the lysosomes (subcellular organelles containing digestive enzymes), thereby causing cells to digest themselves. In addition, acid from the stomach and proteolytic and hydrolytic digestive enzymes naturally present in the body's organs contribute to the decay process. Sometimes the stomach wall decomposes within a few hours of death and consequently its contents enter the peritoneal cavity. This can give the misleading impression that a ruptured stomach contributed to the person's death. Similarly, the pancreas is packed with digestive enzymes, and so rapidly digests itself. Autolysis is not solely a post-mortem phenomenon and may also occur on a more restricted scale in a living person as a consequence of certain diseases.

Decomposing tissues release pigmented chemicals and gasses which make the skin discoloured and blistered, starting on the abdomen in the area above the caecum. Indeed, the skin can be so darkened that a person who had pale skin in life is mistaken for being black, whilst the raised fluid-filled blisters can be mistaken for burns. The front of the body swells, the tongue may protrude, and bloody fluid from the lungs oozes out of the mouth and nostrils. This is accompanied by a terrible smell, as hydrogen sulphide and various sulphur-containing organic molecules (mercaptans) are produced as end products of bacterial metabolism. Methane (which does not smell) is also formed in large quantities and contributes to the swelling of the body. In temperate countries such as the UK, this stage is reached after about four to six days during spring and summer, but takes longer during colder winter weather.

The accumulation of gas results in dramatic rises in the internal body pressure, thereby causing the body to swell and the skin to stretch. This distorts facial features making recognition impossible and gives a misleading impression of obesity (Figure 1.3). The rise in internal pressure distorts and obscures wound sites and can cause the skin to split at weak points such as healing scar tissue. For example, Byard *et al.* (2006a) describe a case in which the body of a

Figure 1.3 Late bloat stage of decomposition. The body is about seven days old and exhibits pronounced swelling owing to accumulation of gas. Note discoloration of the skin and exudates from the mouth and nose. The swelling makes recognition of facial features impossible. Internal pressures force the tongue out, the eyeballs bulge, and the skin splits. *Source*: Reproduced from Payne-James *et al*. (2011), © 2011 Hodder Arnold, London, with permission.

man who had been dead for about 10 days was found with three incised wounds to his lower abdomen and groin. This raised suspicions that he was cut either at the time of death or shortly afterwards. Closer observation of the wound sites revealed suture material and that the incisions did not extend to the abdominal cavity. In fact, the man died naturally of a heart attack. The accumulation of gas during decay process caused the opening of incisions made during bypass surgery four to six weeks previously. The rise in internal pressure is sometimes sufficient to cause the entire skin to split. A possibly apocryphal instance of this occurred in 1547, whilst the corpse of King Henry VIII was transported back to Windsor Castle for burial. His body allegedly swelled to such an extent that his coffin exploded overnight and dogs were found feeding on the exposed remains in the morning. This was deemed to be divine judgement on the king for his dissolution of the monasteries.

1.2.2.2 Putrefactive Rigor

Putrefactive rigor or putrefactive *rigor mortis* arises after rigor mortis has subsided and does not involve changes in muscle tone. It is associated with the accumulation of large amounts of gasses beneath the skin surface because of normal putrefaction. The gasses cause the body to balloon and this distends the limbs and appendages. The internal pressure on the joints results in the body adopting a default pose in which there is 'nearly full extension of the elbow and slight abduction and forward flexion of the shoulder' (Gill and Landi 2011). The upper limbs therefore become raised without any visible support, whilst the upper legs flex upwards. This gives the body the unsettling appearance of being about to deliver a hug or of someone falling backwards into a swimming pool. In males, putrefactive rigor results in a post-mortem artefact known as 'pseudo-priapism', in which the penis becomes erect. This has nothing to do with the normal physiological process of engorgement. Priapism is a medical condition in which the penis remains in a permanently erect state in the absence of sexual stimulation. This is far from desirable and is not only painful but results in serious pathology and potential impotence. Priapism results from a variety of conditions, including diseases such as sickle cell anaemia, scorpion stings, the consumption of aphrodisiacs, and damage to the spinal cord. Consequently, the body of a male found with an erect penis requires a forensic explanation to exclude the possibility of a criminal act.

It is important to distinguish between rigor mortis and putrefactive rigor, because finding a body in an odd position could indicate that it was moved after death. The two forms are distinguishable because rigor mortis occurs shortly after death and subsides before advanced decomposition begins. By contrast, putrefactive rigor occurs through putrefaction and there is marbling of the skin and the stench of decay. Putrefactive rigor may, however, appear soon after death in countries (or situations) with hot moist climates in which decay sets in rapidly (Tsokos and Byard 2012).

1.2.2.3 Adipocere

Adipocere (grave wax or corpse wax) is a fatty substance described as being whitish, greyish or yellowish, and with a consistency ranging from paste-like to crumbly. Extensive adipocere formation inhibits further decomposition and ensures that the body is preserved for many years (Figure 1.4). Adipocere formation is therefore a nuisance in municipal graveyards, because it prevents the authorities from recycling grave plots but useful to forensic scientists and archaeologists who wish to autopsy long-dead bodies.

The term 'adipocere' refers to a complex of chemicals rather than a single chemical compound and it results from the breakdown of body lipids. After death, autolysis and bacterial decomposition of triglycerides, which make up the majority of the body's lipid stores, results in

Figure 1.4 The formation of adipocere has preserved the body of this child, despite it being buried for about three years. *Source*: Reproduced from Payne-James *et al*. (2011), © 2011 Hodder Arnold, London, with permission.

the production of glycerol and free fatty acids. The free fatty acids comprise of a mixture of both saturated and unsaturated forms, but as adipocere formation progresses, the saturated forms predominate. The fatty acids lower the surrounding pH, thereby reducing microbial activity and further decomposition. Adipocere has a characteristic odour, the nature of which changes with time. This smell is used to train cadaver dogs to detect dead bodies. Extensive adipocere formation results in the body swelling. Consequently, the pattern of clothing, binding ropes or ligatures imprints on the body surface, whilst incised or puncture wounds close and become obscured.

Adipocere forms in bodies in many situations, including fresh water, seawater and peatbogs, shallow and deep graves, tightly sealed containers, and in bodies buried but not enclosed at all (Evershed 1992; Mellen *et al*. 1993). Some workers state that warm conditions (21–45 °C) speed its formation, but adipocere develops on bodies in seawater at 10–12 °C and icy glaciers (Ambach *et al*. 1992; Kahana *et al*. 1999). Indeed, the preservation of the 5300-year-old 'Iceman' ('Ötzi'), discovered in the South Tyrol region, is at least partly because of adipocere (Bereuter *et al*. 1997).

Tissues with high lipid content are more prone to form adipocere. Clothing that absorbs and retains moisture facilitates adipocere formation in both terrestrial and aquatic conditions (Notter and Stuart 2012). Most authors emphasise the importance of anaerobic conditions and anaerobic bacteria such as *Clostridium* species for the formation of adipocere.

The time required for extensive adipocere formation is case-dependent, with reports citing durations ranging from days to months to over a year. Therefore, it is impossible to use adipocere formation as an estimate of the PMI. However, because adipocere leaks out of the body, its presence in the soil can indicate post-mortem movement. For example, if the amount of adipocere in the underlying soil is commensurate with the state of decay of the body, then it suggests that the body rested in its current position since death. By contrast, if there is extensive adipocere formation in the body but little adipocere in the soil, it is possible that the body was moved there recently. Alternatively, the presence of adipocere in the soil but the absence of a body suggests that a body rested there for a while before it was moved. Once formed, adipocere persists for many years. The disappearance of adipocere is associated with exposure to oxygen and therefore to aerobic microbial decomposition.

1.2.2.4 Mummification

Strictly speaking, the term 'mummification' should be restricted to the intentional use of chemicals to dry out a body's soft tissues and thereby preserve them. The term 'mummy' derives from the Persian '*mummia*', meaning 'wax'. The word also referred to the bitumen or pitch used by ancient civilisations to preserve dead bodies. Currently, the term 'mummified' implies that a body or part of a body is dry – whether through natural causes or chemical treatment.

Natural mummification results from exposure to dry conditions coupled with extreme heat or cold, especially if there is also a strong air current encouraging evaporation of water. In the process, the skin becomes extremely dark and leathery. Mummification of the whole body typically takes about 6–12 months, but is more rapid under extreme environmental conditions. It occurs in persons who die in deserts, such as the hot Sahara and the cold Tibetan plateau, murder victims bricked up in chimneys and persons who die in dry well-ventilated areas (Figure 1.5a and b). Partial mummification of exposed peripheral body parts (e.g. ears, fingertips, and toes) occurs in dead bodies left outside in cold weather or stored in a mortuary. Patel (2003) describes a case in which the skin overlying the scrotum of a dead man dried out

(a) (b)

Figure 1.5 (a) The body of this man was discovered 5.5 months after he committed suicide in a disused warehouse. The ligature is still around his neck. His body and hair are preserved extremely well, indicating that the warehouse was well ventilated, but rodents and insects were absent. *Source*: Reproduced from Kerr (1957). (b) Mummified fingertip. The drying and retraction of the surrounding skin makes the fingernail appear longer and hence the common perception that after death nails continue to grow. The drying of the skin makes fingerprinting difficult or impossible. *Source*: Reproduced from Dolinak *et al*. (2005), © 2005 Elsevier Academic Press, with permission.

(this is referred to as parchmenting) and as consequence was discoloured. The dry region bore a superficial resemblance to a bruise. Blows to the scrotum are excruciating and potentially fatal if they induce a heart attack through vagal inhibition. It was known that the man had been in a fight three days before he died, in the course of which he had stabbed another man. It was therefore important to establish whether the 'wound' to the scrotum related to his death – for example, he might have suffered a revenge attack. Dissection of the scrotum demonstrated that there was no release of blood into the surrounding tissues. Therefore, it was not a bruise and there was no indication of any wounds. The autopsy conclusion was that the man suffered from numerous pathological conditions, including coronary artery disease and he died of non-suspicious heart failure.

Size is an important factor in the development of mummification, and dead babies and young children, owing to their large surface area to volume ratio, lose water more rapidly than an adult does. Newly-born babies lack an active gut microbial flora and therefore not only do they lose water quickly, they may dehydrate before microbial decomposition can cause major destruction of tissues. Abrasions also dry out rapidly, because there is no overlying skin to reduce the rate of water loss. Once a body desiccates, it can remain intact for thousands of years if left undisturbed in a dry environment and insects capable of consuming dry organic matter (e.g. dermestid beetles and the larvae of tineid moths) do not gain access to it. However, a mummified body exposed to moist air absorbs water and rapidly suffers fungal and bacterial decay.

1.2.3 Putrid Dry Remains

After the loss of the skin and soft tissues, a body is reduced to the hard skeleton and structures composed of stable complex molecules that are resistant to decay, such as the tendons, ligaments, fingernails, and hair. The uterus and prostate glands are also fairly resistant to decay and last for several months if the body is in a well-sealed container. As long as traces of slowly decomposing organic matter are left, a skeletonised body continues to smell of decay.

Bones undergo a decay process referred to as diagenesis, and their chemical composition and microscopic structure changes because of microbial attack and environmental exposure. Bone decay begins soon after death and bacteria invade bone via its natural pores (Jans *et al.* 2004). Significant changes are therefore already apparent by the time of skeletonisation and invasion by soil bacteria is probably not of major importance. Inevitably, bones closest to the abdominal cavity tend to exhibit the most marked microbial attack (Table 1.2).

Table 1.2 Summary of the stages of decomposition and their characteristic features.

Stage of Decomposition	Characteristics
Fresh	Body starts to cool and autolysis begins. Hypostasis and rigor mortis may be seen.
Bloat	Discoloration of skin surface, body swells from accumulation of gasses. Tongue protrudes, fluid expelled from orifices. Soft tissues visibly decaying. Rapid decay owing to intense microbial and invertebrate activity.
Putrefaction	Progressive loss of skin and soft tissues. Body deflates as decomposition gasses escape. Decay owing to invertebrate and microbial activity starts to slow down once soft tissues removed and body starts to dry out.
Putrid Dry Remains	Skin and soft tissues lost. Decay proceeds more slowly. Progressive loss of uterus/prostate gland, tendons, cartilage, fingernails, hair. Skeleton becomes disarticulated through environmental and biological processes.

1.3 Factors Affecting the Speed of Decay

The rapidity and extent to which a corpse is colonised by the larvae of blowflies, along with the activities of other invertebrates, microbes, and vertebrates, heavily influences the speed with which a body decays. Consequently, those factors that restrict their access or reduce their activity, such as physical exclusion, lack of oxygen or the temperature being too low or too high, reduces the rate of decomposition enormously – see Zhou and Byard (2011) for some case examples.

1.3.1 Detritivores

The odours of blood and decomposition attract blowflies and other detritivores, and as the smell changes during the decay process, so does the species of invertebrates attracted. Therefore, 'fresh corpses' attract different detritivores to corpses in an advanced state of decay (Table 1.3). Blowflies will lay their eggs on bodies within seconds of death occurring, but do not lay eggs on dry or mummified remains. By contrast, trogid beetles do not usually colonise corpses until these have started to dry out.

1.3.2 Geographical Location: Temperature and Humidity

Geographical location, whether on the scale of countries, regions within a country or inside buildings, has a major impact on the speed at which a body decomposes. This is principally through its influence on temperature and humidity. The growth of all organisms

Table 1.3 The sequence in which insects arrive and colonise a corpse during the decomposition process.

Stage of Decomposition	Insect
Fresh	Blowfly eggs and 1st instar larvae Fleshfly 1st instar larvae Burying beetle adults
Bloat	Blowfly eggs + 1st, 2nd, 3rd instar larvae Fleshfly 1st, 2nd, 3rd instar larvae Burying beetle adults and larvae Histerid beetle adults and larvae
Putrefaction	No blowfly eggs once advanced putrefaction Blowfly 2nd, 3rd instar larvae Fleshfly 2nd, 3rd instar larvae Blowfly and fleshfly larvae leaving corpse for pupation site Histerid beetle adults and larvae Eristalid fly larvae (liquified regions) Phorid fly larvae (later stages of putrefaction) Piophilid fly larvae (later stages of putrefaction))
Putrid Dry Remains	No blowfly larvae Stratiomyid fly larvae Dermestid beetle adults and larvae Tineid moth larvae Pyralid moth larvae

Note: The stages of decay merge into one another and the insects may arrive or leave earlier or later than indicated in the table depending upon the individual circumstances.

takes place within relatively narrow temperature limits. Even if the temperature is suitable, an organism may not survive if the humidity is too low or too high. Consequently, geographical location on both a macro- and a micro-scale affects species composition and abundance of organisms that are able to exploit the body and the rates at which autolytic reactions take place.

Decay processes proceed extremely quickly in hot humid regions. In the tropics, there is a large community of invertebrate decomposers and the high humidity facilitates the growth of fungi and bacteria. Consequently, a corpse can become a moving mass of maggots within 24 hours and reduced to a skeleton in less than a fortnight. By contrast, in temperate climates, it may take several days to reach the bloat stage, even during the summer.

Temperatures that are very high or very low and climates that are very dry, restrict the activity of invertebrates and microbes and thereby reduce the rate of decay. A body left in freezing conditions, such as high on a mountain, in a glacier, or the Arctic, is preserved for as long as the conditions remain below zero. For example, carcasses of woolly mammoths with excellent soft tissue preservation are found in the Arctic tundra, despite dying thousands of years ago. The consequences of freezing vary between tissue types, with some hardening (e.g. skeletal muscle) and others softening (e.g. brain) when they subsequently warm up.

1.3.3 Time of Year

As mentioned previously, decomposition proceeds most rapidly in warm damp environments. Consequently, in European temperate climates, a body exposed to the outside environment decays faster during the summer months than during winter. This is partly owing to the effect of the environment on the rates of autolytic and microbial decay and partly through invertebrate detritivores, not only being affected by temperature but also showing patterns of seasonal activity.

Although many invertebrates are seasonal, cities and large towns offer warm microclimates that facilitate their continuous growth and reproduction during the winter months. For example, the housefly *Musca domestica* does not exhibit diapause and is unable to survive freezing temperatures. However, populations exist even in far Northern Europe, due its ability to exploit warm microclimates associated with human dwellings. Similarly, during winter, blowfly species that are inactive in the surrounding countryside may remain active in urban areas.

1.3.4 Exposure to Sunlight

The effect of exposure to sunlight upon decay is case dependent. Warming by the sun's rays promotes bacterial decay and autolysis, but if there is low humidity and a strong wind, the body would desiccate and mummify, thereby retaining much of the its integrity. A body exposed to the sun is usually visible and the odour of decay detectable by both vertebrate and invertebrate detritivores. This leads to the body becoming dismembered and consumed and/or colonised and consumed. Invertebrates avoid laying their eggs on and colonising regions of a corpse exposed to the full sun. This is because the combination of desiccation and UV light would kill their delicate eggs and larvae. However, eggs laid on the under surfaces or beneath clothing or other coverings (if they are not too tight to restrict access) will be protected from the sun and have a more humid microenvironment. This facilitates microbial and maggot growth and consequently these covered regions may decay more rapidly than exposed body parts. However, a lot depends on the nature of the covering material.

1.3.5 Wrapping and Confinement

Persons disposing of a dead body often wrap or otherwise cover it up to make its transport easier and reduce the risk of its subsequent discovery. Metal foil is sometimes used, as is plastic sheeting, bubble wrap, dustbin bags, and cling film. 'Wrapping' is also a sexual fetish activity. Usually, the intention is to induce controlled non-lethal asphyxiation but accidents happen and the participant dies (Schellenberg *et al.* 2007). Therefore, a body found wrapped in bin liners or confined in a large case may not indicate criminal activity. The investigators must check whether the person could have got into the situation unaided and whether there are other suspicious signs such as wounds to the body. If it is a 'fetish gone wrong', other evidence is often present, such as fetish clothing and pornographic material. The victim's past computer search history also provides an indication of their predilections. 'Wrapping' also describes covering a person's head with a plastic bag to cause serious harm or death (Byard *et al.* 2006b). For example, it is used to torture and kill people and as a means of committing suicide. In the case of homicide, there will often be evidence of bruising and restraint. For a case report, see Saint-Martin *et al.* (2009).

Corpses are sometimes wrapped within carpets, but this must make movement extremely difficult, because any carpet large enough to conceal a body is already a heavy, bulky object. Corpses are also found in the boots of vehicles, placed in suitcases or similar large containers, left within locked rooms, placed under floorboards or in loft spaces, or bricked up. All of these scenarios have their own individual effects on the rate of decomposition. However, the common factor is that the rate of decay is slowest where the covering is most effective at excluding oxygen, vertebrates, and invertebrates.

Regardless of the scenario, unless the temperature is below freezing, a body will start to decay and the smell attracts detritivores. Flies usually find their way into a locked car boot and lay their eggs through the zips of suitcases (Bhadra *et al.* 2014), whilst dogs and foxes will bite and claw their way through plastic wrapping. If detritivores cannot gain access to the body, it decays slowly, thereby preserving evidence for longer. Murder weapons and other evidence is often enclosed or entombed with the body. Even if a body is encased in concrete, the smell of decay may still be detectable. Furthermore, when someone goes missing and a suspect starts mixing concrete, it is not long before suspicions are aroused (Preuß *et al.* 2006). Interestingly, analysis of the composition of the concrete (a process known as petrography) can enable determination, not only of where and when the concrete was sourced, but also how old it is and thereby, by inference, the PMI. For example, an unusual case arose in USA in which the body of a young woman was found entombed within a homemade concrete sarcophagus (Morel 2004). Petrographic analysis identified not only the type of concrete but that it was made within a narrow range of about 1.5–2 years previously. By contrast, anthropological analysis of the woman's remains could only place the time of death as some point between two and seven years previously. It was also possible to link the sarcophagus with a concrete spattered retractable utility knife found nearby, that was the probable murder weapon.

1.3.6 Burial Underground

Buried corpses reportedly decay four times slower than those left on the surface, and the deeper the burial, the slower the decay (Dent *et al.* 2004). However, as with bodies left above ground, the rate of decay of a buried body is affected by a wide range of variables. The nature of the soil affects the rate of decay directly through chemical actions and indirectly through its effect on the abundance and activity of soil organisms. Microbial density varies enormously with the soil type, but figures are generally in the region of $2 \times 10^9\ g^{-1}$ in the top metre and $10^8\ g^{-1}$ at a depth of 1–8 m (Coleman *et al.* 2004). Heavy clay soils are poorly aerated and therefore have low oxygen levels and this reduces microbial activity and hence the rate of decay. Acid soil reduces microbial activity, but the low pH dissolves soft tissues and bone. High soil calcium content reduces chemical dissolution of bones, but microbial decomposition will still take place. The temperature and moisture content of the soil also affect the speed of decay. Therefore, factors such as the time of year, exposure to the sun, rainfall, and depth of burial, soil chemistry, drainage, and the height of the water table, all influence the rate of decay.

Even a few centimetres of soil usually prevents blowflies from colonising a buried body and hence reduces the rate of decomposition. However, a variety of other invertebrates exploit buried remains (Gaudry 2010). For example, some fly species lay eggs on the soil surface and the larvae then burrow to the corpse (e.g. *Muscina stabulans*) or the adults crawl through cracks in the soil to reach and lay their eggs upon it (e.g. *Conicera tibialis*). Shallow buried bodies may be detected and dug up by dogs, foxes or badgers, and in these instances it is probable that the body will be dismembered: it will also allow blowflies and other insects greater access to the body. Corpses are often wrapped or enclosed in something before burial. This further reduces the rate of decay, dependent upon the degree to which they are airtight and exclude detritivores.

1.3.7 Hanging above Ground

Bodies become suspended above ground as a result of suicidal or homicidal hanging (lynching), although they may also end up within trees as a result of being hurled there by an explosion, thrown from a vehicle after a crash, or knocked there after being hit by a train or vehicle. A body that is left hanging above ground may decay more slowly than one that is lying on the surface of the ground (Wyss and Cherix 2004). This is probably because a body suspended in mid-air has no moist, dark, under-surface where flies can lay their eggs, the circulation of air promotes drying out, and many maggots fall off whilst crawling around or become washed off by the rain.

1.3.8 Burial Underwater

It is sometimes stated that bodies decay twice as slow in water than they do in air, but this is a gross generalisation. Aquatic environments are extremely diverse and can encompass everything from nutrient poor pristine alpine streams to eutrophic ponds and from seashores to abyssal depths through to wells, slurry pits, and Jacuzzis. Many aquatic environments have a lower temperature than terrestrial habitats and both temperature and oxygen tension decline with depth; both these factors will inevitably reduce the rate of decay. However, in some instances, the surface water temperatures of both freshwater ponds and marine ecosystems can be over 20 °C for extended periods. Therefore, they are not always 'cold'.

Bodies are said to decay more slowly in the sea than they do in freshwater because seawater contains fewer marine micro-organisms. In truth, there is little experimental data on decay rates in marine environments and surface seawater contains similar bacterial densities to those of lakes (10^6 ml^{-1} cf. 10^5–10^7 ml^{-1}), whilst microbial populations in sediments, even at great depths, are much higher than previously thought (Azam and Malfatti 2007). The rate of decay will also depend upon the abundance of aquatic invertebrate and vertebrate detritivores (Anderson 2010). Crabs and fish remove soft tissues from a body, whilst sharks, alligators, and crocodiles will dismember a body or consume it entirely.

Unless firmly weighted down, bodies buried underwater usually float up to the surface when gas formation occurs. Bodies floating on the surface of ponds, lakes and rivers can be colonised by blowfly larvae and this, along with the exposure to higher temperature and oxygen levels (than underwater), increases the rate of decomposition. Blowflies do not occur at sea, although they colonise bodies washed up on beaches. A floating body attracts seagulls, skua, and other scavenging birds, which rapidly remove soft tissues.

1.3.9 Wounds

Wounds, whether inflicted at the time of death or immediately afterwards, allow entry of air and invertebrates into the body and therefore speeds up decay. The smell of blood attracts blowflies and a range of insect detritivores and vertebrate scavengers. This leads to rapid discovery and exploitation of the body. However, if blood loss is severe, it slows microbial colonisation of the body (or parts of the body if dismembered). This is because the microbes are no longer able to grow through the liquid medium of the blood vessels. Extensive blood loss and evisceration also facilitates desiccation and therefore preservation of the remaining soft tissues.

1.3.10 Infections

Pre-existing infections, such as septicaemia or infected wounds, can speed up the rate of decay, because there are already bacteria colonising and breaking down the body at the time of death. For example, Paulino *et al.* (2012) describe a case of a man who died in hospital from a serious *Clostridium perfringens* infection, whose body exhibited extensive signs of decomposition within 12 hours of death, despite being stored in a mortuary.

1.3.11 Burning

Murderers often attempt to dispose of their victim's body by burning it. However, they are seldom completely successful, owing to the extremely high temperatures required. Identifiable human remains persist among the ashes produced by a crematorium, which typically operates at over 1000 °C for two to three hours. The temperatures reached in typical house fires are much lower than this and, although they may exceed 700 °C, this tends to be for relatively short periods and occur close to the ceiling. On the floor, the temperature may only reach 166 °C – although a lot depends on the presence of combustible material. Nevertheless, victims of house fires, explosions, and traffic and aircraft accidents are often badly burnt. Usually, the extremities, the limbs and the head are most badly affected and the torso is the last part of the body to be fully consumed. Bodies with a high fat content burn the best and clothing, provided it is flammable, will contribute to the extent to which the body is destroyed. Sometimes the body is placed in a tyre that is then set alight as a means of providing extra fuel.

Some factors associated with burning reduce the rate of decomposition, whilst others promote it, so it is difficult to generalise. For example, burning sterilises the skin surface and dries the underlying tissues, making them unsuitable for the growth of microbes and blowfly maggots, but it also causes cracks through which they may invade the deeper tissues that are less affected. Similarly, although the skin surface may be charred, the core body temperature may not rise sufficiently to affect the gut microbial flora. Therefore, decomposition may commence in the abdomen as normal. Some workers state that burnt corpses retain their attractiveness to blowflies, whilst others find that it reduces their likelihood to lay eggs on the body (Avila and Goff 1998; Catts and Goff 1992). Obviously, a great deal depends on the degree of burning and the individual circumstances. Gruenthal *et al.* (2012) found no difference in the rate of decomposition of untreated and charred pig corpses, although flies were attracted to the most heavily charred regions.

Burning induces chemical changes in proteins, carbohydrates, lipids, and other organic molecules. This will influence the ability of burnt tissues to support microbial and maggot growth. However, currently there is little published information on this in a forensic context. Nevertheless, there is information on how storage and cooking affects the chemical composition and palatability of meat destined for human consumption (Varnam and Sutherland 1995). Basically, when meat is cooked, it causes the fats to melt and therefore they become susceptible to degradation (e.g. triglycerides break down to glycerol and fatty acids) and oxidation (e.g. the carboxylic acid group of a fatty acid chain is oxidised). The oxidation of fatty acids produces a range of chemicals that contribute to the smell of cooked meat and also undergo reactions with other chemicals to produce compounds that contribute to the taste of meat. Heating above 40–50 °C causes proteins to denature (their three-dimensional shape changes) and hydrolyse (break down). As the temperature rises, more and more proteins are affected. Denaturation causes muscle proteins to contract (hence heat stiffening) and in the process, the cytoplasm of the muscle cells is forced out. Other proteins are also denatured causing further shrinkage, loss of fluid contents and therefore the tissues dry out as the water evaporates. As the temperature rises, pyrolytic reactions occur. Pyrolytic reactions are those in which heat causes compounds to convert into one or more products. For example, collagen converts into gelatine. The breakdown of proteins results in a rise in the concentration of amino acids and some of these react with sugars in the complex, non-enzymic, Maillard reaction. This is important in the development of flavour. However, humans and detritivores do not necessarily find the same things attractive or flavoursome. If heating is prolonged, the body becomes desiccated and if the temperature is high enough, it becomes carbonised and turns black as all the organic matter is lost.

1.3.12 Chemical Treatment

Murderers occasionally cover their victim's body with chemicals in order to enhance its speed of decay, reduce its likelihood of detection or destroy potential incriminating evidence. It is a common belief that covering a body with quicklime or slaked lime leads to its rapid and total destruction. In fact, it contributes to the body's preservation. Quicklime (calcium oxide [CaO]) reacts with water to produce corrosive slaked lime (calcium hydroxide [$Ca(OH)_2$]) in a highly exothermic reaction (i.e. a lot of heat is produced). Indeed, the reaction generates so much heat, it causes localised desiccation. Experimental work with buried dead pigs demonstrates that both quicklime and hydrated lime delay the onset of decay by several months, but once dug up the bodies become colonised blowflies (Schotsmans *et al.* 2012).

Placing a body in an acid bath destroys all the soft tissues as well as the bones. However, the speed and effectiveness are affected by the water content of the tissues; fat is hydrophobic and not readily solubilised.

1.3.13 Embalming

Embalming is the process by which a dead body is treated with chemicals to delay or prevent its decomposition. The ancient Egyptians, among others, embalmed their dead for religious reasons and sought to prevent decay entirely. Similarly, Vladimir Lenin's embalmed body is on public display in his Moscow tomb. Nowadays, at least in Europe and USA, embalming is not done for religious or political purposes, but to temporarily preserve the body so that it remains presentable and not a danger to health until it is buried or cremated. In the USA, embalming is so common that concerns have been raised that leakage of embalming fluid from buried bodies might lead to contamination of groundwater. In Europe, embalming practice varies enormously: for example, it is relatively common in the UK and France, rarely used in Germany, and prohibited in Belgium and Denmark.

In the UK, embalming usually involves infusing the body with a 2% solution of formaldehyde, although the embalming fluid may contain a variety of other chemicals, such as phenol. This is preferably done within 36 hours of death. The forensic relevance of this is that embalming can compromise the subsequent chemical analysis of the body's fluids and tissues. Obviously, forensic samples should be taken before embalming occurs, but this is not always possible or the need is not recognised at the time. For example, the embalming of Princess Diana's body after her death in a car crash on 31 August 1997 prevented hormone analysis that would have proved whether she was pregnant with her lover Dodi Fayed's child. Needless to say, this spawned a 'cover-up' conspiracy theory. Embalming introduces artefacts, such as methanol, so it is helpful to have a sample of the embalming fluid to confirm whether this was the source. Blood ethanol levels may be reduced or impossible to assay following embalming, but at least for the first four days afterwards a reliable estimation of the ante-mortem levels can be made by measuring the levels in the vitreous humour – provided the eyes were not injected with a mixture that compromises the analysis. By contrast, some chemical analyses, such as those for morphine and strychnine, are not affected by embalming.

Drug users sometimes add embalming fluid to marijuana before smoking it. The preparation is then known as 'water', 'wet' or 'fry'. Users state that it gives them a 'numbing buzz and a fiery feeling in the lungs' (Chlebowski and Leonard 2012), but it also puts them at risk of serious disease, because formaldehyde is not only toxic but carcinogenic. In the body, formaldehyde is metabolised to formic acid (formate) and this is detectable as elevated levels in the blood and urine. However, low levels of formic acid are naturally present in the body and it forms during putrefaction (Viinamäki *et al*. 2011).

1.3.14 Summary of Factors Promoting or Delaying the Rate at which a Body Decays

From this brief overview, it can be seen that a wide range of factors (Table 1.4) affect the decay of a body. Furthermore, many of these factors interact and vary in their duration. Consequently, decay is a complex, ever-changing process and one must be aware of how these can influence the preservation and interpretation of forensic evidence.

1.4 Future Directions

Advances in separation techniques, such as high performance liquid chromatography (HPLC) and gas chromatography (GC), and detection methods, such as mass spectrometry (MS), means that one can analyse simultaneously a wide range of metabolites. This forms the basis of a comparatively new area of study called metabolomics. This involves profiling the hormones, messenger molecules, metabolites, secondary metabolites and small molecules with a molecular weight of less than 1000 Da present within a sample. Metabolomics is a natural partner to next generation sequencing (NGS) and epigenetics and increasingly used for researching the physiological basis of health and disease. Metabolomics has many potential applications in

Table 1.4 Summary of factors promoting or delaying the rate at which a body decays.

Factors Promoting Decay	Factors Delaying Decay
Oxygen supply not restricted	Oxygen supply restricted
Warm temperature (15–37 °C)	Cold temperatures (<10 °C; decay ceases below 0 °C)
Humid atmosphere	Dry atmosphere
Presence of invertebrate detritivores	Absence of invertebrate detritivores
Dismemberment by vertebrates	Protection from vertebrates
Wasp, ant and other invertebrate predators feeding on corpse	Wasp, ant and other invertebrate predators feeding on detritivores
Wounds permitting invertebrates easy access to internal body tissues	Inability of detritivores to gain access to all or part of the corpse
Surface burning causes skin to crack thereby allowing easy access for invertebrates and oxygen to internal tissues	Intense burning causes tissues to dry out and carbonise
	Body suspended above ground (e.g. hanging)
Body exposed above ground	Burial on land or underwater
Body resting on soil	Formation of adipocere
Obesity	Mummification
Suffering from septicaemia or myiasis before death	Embalming

forensic science and in particular for detecting drugs and poisons (Castillo-Peinado and de Castro 2016). It might also prove useful for understanding the physiological processes taking place after death under different taphonomic conditions. This could lead to the identification of an algorithm based on physiological parameters for the determination of the PMI.