Review of human decomposition processes in soil

B.B. Dent · S.L. Forbes · B.H. Stuart

Abstract In-soil human decomposition is comprehensively described in terms of the physico-chemical and bacterial environmental conditions. Much of the understanding comes from considerations of cemetery studies and experimentation with adipocere. The understandings are relevant for further studies in cemetery management, exhumations, forensic investigations and anthropology. In the soil, cadavers are subject to various sets of decomposition processes principally resulting from aerobic (usually the initial) or anaerobic (usually the sustaining) conditions. The presence of percolating groundwater and microorganisms further affects the rate of breakdown and fate of the products. The major human tissue components—protein, carbohydrate, fat and bone, are discussed; and the likely pathways of decomposition products enumerated. The effects of liquefaction, availability of oxygen and other in-grave processes are considered.

Keywords Human decomposition · Cemetery · Adipocere · Grave soils · Exhumation

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Introduction

The authors' current research into aspects of the operations of cemeteries and their impacts on the environment, and the chemistry of the post-mortem product—adipocere, have necessitated a lengthy consideration of human decomposition processes. The information about these processes, in general, is widely dispersed and available, but is usually slanted at the particular aspects being discussed. However, the discussion of decomposition in soils has been largely untreated in detail, and the fragments available are often incomplete. There are important summaries of the main aspects—Mant (1957, 1987); Corry (1978); Janssen (1984); Polson and others (1985); Clark and others (1997); Gill-King (1999).

Large-scale human decomposition processes are typically associated with cemeteries; these have been shown to be best interpreted as special kinds of landfill (Dent 1995, 2002; Knight and Dent 1995; Dent and Knight 1998). Hence this review is relevant for further studies on cemetery location. In recent studies Santarsiero and others (2000) used limited considerations of decomposition processes to review Italy's cemetery re-use needs and work is also actively being pursued in this context in Brazil (Pacheco personal communication 2000). Moreover, there are other interest areas in the forensic and anthropological sciences such as further studies on death scene interpretation, particularly after some years of burial; studies in forensic contexts particularly using buried pigs, and exhumations and the context of interred remains generally. The use of pigs in relevant studies (Forbes and others 2002, 2003; Forbes 2003) has been shown to mimic the decompositional biogeochemistry of human beings.

Decomposition processes

Previous authors have diverged in the presentation of the order in which the various processes occur, and display a little variation in the manner of these, but these differences are possibly not too serious in the overall interpretation. In respect of discussions about individual processes and their effects, these are very dependent upon the individual circumstances being described, for examples see Janaway (1993, 1997), Galloway (1997), and Owsley and Compton

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(1997). Forbes and others (2002, 2003) and Forbes (2003) have studied adipocere formation as an aspect of decomposition and have provided some important additional insights.

Even when considering aspects of burial in soil, it needs to be borne in mind that remains interred within a coffin will initially begin to decompose differently, in some respects, to those which are in intimate contact with the soil from the outset, such as in a clandestine grave. The soil, being a complex assemblage of minerals, organic matter, salt and organic solutions and various microscopic and macroscopic organisms will also exert varying influences in various locations and burial situations. With the passage of time, it is most usual for wooden or similar coffins to decay away after initial collapse to various degrees. Sometimes, the collapse of coffin lids occurs soon after interment and thus the remains are intimately associated with the surrounding soil, while oxygen and decomposition gases are rapidly dispersed. For the typical, coffinated burial, this is the expected pattern but usually on a longer timescale. A timescale which is so far proving very difficult to quantify but has nevertheless been attempted by Forbes (2003), and Forbes and others (2003).

Decomposition commences almost immediately after death and is characterized by spontaneous postmortem changes. Soft tissue that has not been naturally or artificially preserved is subject to the postmortem processes of autolysis and putrefaction. Following putrefaction, the decomposition process continues through liquefaction and disintegration, leaving skeletonized remains articulated by ligaments. Skeletonization proceeds until eventually only the harder resistant tissues of bone, teeth and cartilage remain. These remains are then subjected to inorganic chemical weathering (Fig. 1).

Putrefaction is characterized by the bacterially induced breakdown of soft tissue and subsequent alteration of their protein, carbohydrate and fat constituents. Van Haaren (1951) indicated that the body composition is approximately 64% water, 20% protein, 10% fat, 1% carbohydrate and 5% minerals. The breakdown results from the action of bacteria and enzymes that are already present in the tissues, or enzymes that are otherwise derived from in-soil microorganisms and fungi (Evans 1963; Polson and others1985). A large proportion of the decomposition products should reflect the amount of protein and fat contents of the remains.

Normally, putrefaction is initiated by autolytic processes (Janssen 1984) and is generally not observed until at least 48–72 hours after death. The time frame for putrefaction to occur can vary depending on the surrounding environmental conditions, but is the most likely in-grave decomposition process. After death, the microorganisms present in the intestines and respiratory tract invade the body tissues. Aerobic organisms deplete the body tissues of oxygen as well as setting up favorable conditions for the anaerobic microorganisms that take the remains through the putrefactive stages. These anaerobic organisms are usually derived from the intestinal canal but may also migrate from the soil and air into the remains in the later stages of decomposition (Evans 1963).

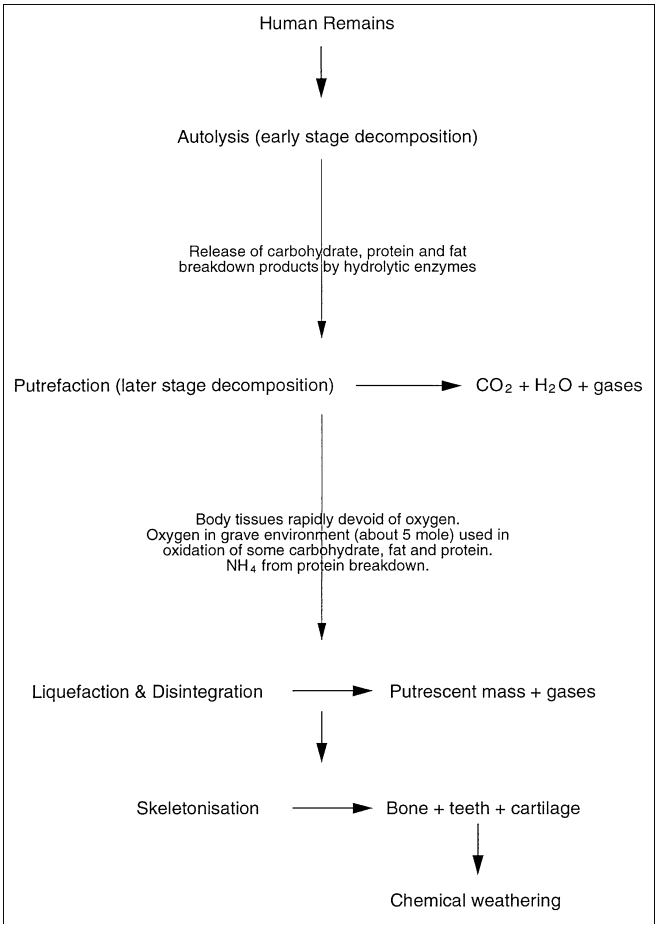

Fig. 1
Overview of human decomposition processes

An oxygenated environment will increase the rate of decomposition. It has been noticed for example that bodies lying in wooden coffins will putrefy much more rapidly than those in leaden shells, due to the freer access of air to the body as the wood coffin disintegrates (Lewis 1851; Mant 1957, 1987; Evans 1963; Henderson 1987). However, in the grave, the amount of oxygen available to the remains is limited and its continual involvement depends on gas diffusion in the grave and attendant soils. Fungi are commonly found on the skin and exposed surfaces of decomposing remains. In some cases they can also be found growing in the intestines and other body cavities. However most fungi encountered are aerobic and are therefore restricted to surfaces whereby little or no penetration of the tissue takes place. In a sealed coffin, the fungal growth is usually slowed and arrested due to the reducing conditions present (Evans 1963).

Availability of oxygen

During the autolytic process, a hydrolytic splitting of proteins, carbohydrates and fats occurs (Janssen 1984). At this stage, oxidative processes may occur within the

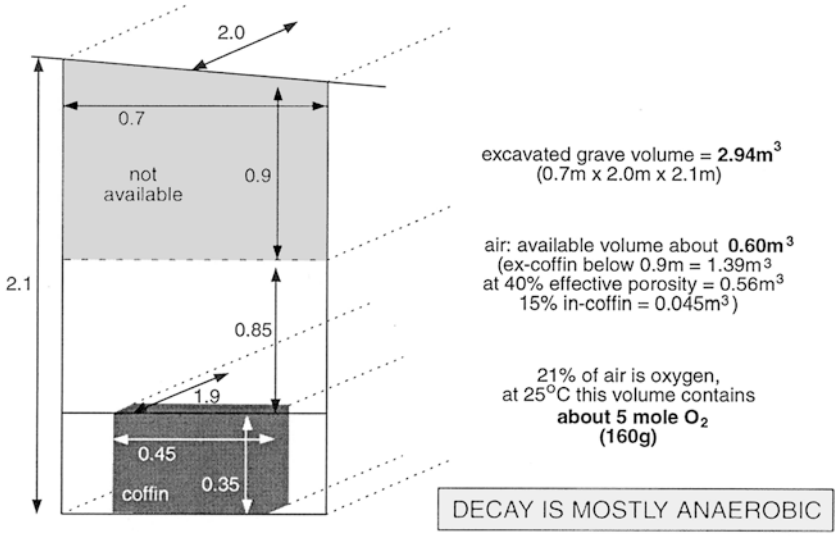

Fig. 2
Oxygen availability for in-grave decomposition

decomposition environment but require oxygen availability.

In a grave, as illustrated in Fig. 2, this availability is highly restricted. The data for grave size are derived from a composite of representative sizes examined in Australia (Dent 2002); however, these, like any of the details of the model can be manipulated by small degrees to skew the discussion but suffice here to illustrate the concepts. The percentage of available airspace in the coffin is nominal. Because the usual physical procedures of interment require a hole to be excavated, the remains (encapsulated or not) emplaced, and then backfilling with site soils, there is a considerable disruption to the normal gas (and water) infiltration and diffusion pathways into the grave. At the commencement of the procedures the diffusion/infiltration is easy and unobstructed, excess of the atmosphere is present at the grave invert; however, as backfilling proceeds, air is progressively displaced and excluded by soil. The soil is, in the typical model, looser than that surrounding the grave (grave walls) even if wetted-down to increase its compaction, so that its effective porosity and permeability are both greater than equivalent undisturbed material.

Accordingly, excess oxygen (as 21% of air on average) is entrapped close to the coffin and certainly in the lower parts of the backfill. Closer to the grave's surface level the density of the soil fill increases: this is as a result of the physical presence of gravediggers completing the backfill or because of machine tamping (e.g. a backhoe bucket used to induce compaction by battering). In the latter case the machine is careful not to be directly in contact with the coffin. The density increase is certainly carried out by design. Therefore, in the model (Fig. 2) the upper soil volume is considered to make little contribution of oxygen available for consumption in a short timeframe.

It could be expected that oxygen availability would be higher than that for the natural soil or for other graves where there is a relative equilibrium of compaction and finalization of decomposition. The corollary to this is that when the interment is complete, the soil compaction processes continue of their own accord and are aided by infiltrating rainfall and subsequent water percolation. Except for very special grave systems and vaults, it is most unusual for a grave's surface to be completely sealed over in a short timeframe.

In typical studies of the unsaturated zone, workers are usually little concerned with oxygen diffusion beyond one metre depth as it decreases rapidly, regardless of soil porosity (Bouwer and Chaney 1974; Domenico and Schwartz 1990). Oxygen dissolved in groundwater itself is another source of the gas for decomposition reactions. It is, however, near impossible to determine how much of any percolating groundwater will directly contact the decomposing remains or to predict the aerobic state of any waters when they first reach such remains. Moreover, except for continuous rainfall from the commencement of interment, the grave soils are likely to be less than saturated and not receiving copious percolation quickly. As the depth of percolation increases the dissolved oxygen will be less and less inclined to leave its hydrated state; thus it will be more readily available for in-solution reactions and for reaction with soil particles at the edge of any water film or droplet rather than as a free phase.

Calculations for the grave model suggest that only about 150–200 g (about 5 mole) of oxygen gas is available for short timeframe, chemical decomposition (decay) processes, and any direct respiration needs of microorganisms. Consequently, it is clear that in-grave decomposition processes are mostly anaerobic after a very short period of time.

There is an important opposing effect to also consider. With time, and for variable amounts of time, decomposition gas products like carbon dioxide, methane, hydrogen sulfide, ammonia, cadaverine and putrescine, diffuse upwards from the remains; preferentially in the looser soils of the grave volume. These gases will compete for space with oxygen diffusing downward with unknown effects; suffice to expect the blocking of downward diffusion and

displacement of entrapped gases (e.g. air) upwards. These aspects have scarcely been studied.

Decomposition products of protein

After death, proteins are broken down by the action of enzymes via a process known as proteolysis (Evans 1963). This process does not occur at a uniform rate and hence some proteins are destroyed in the early stages of decomposition while others are destroyed in the later stages. The proteins of the neuronal and epithelial tissues are usually the first to be destroyed, including the lining membrane of the gastro-intestinal tract while those that are more resistant to decomposition, include epidermis, reticulin, collagen and muscle protein.

Keratin, an insoluble fibrous protein found in skin and hair is resistant to attack by most proteolytic enzymes. The integrity of this substance—which is the reason that hair remains among skeletonized remains for a long time—is due to the disulfide bonds between its component cystine structures. Its destruction is eventually aided by physical or microbial damage; *Streptomyces* spp. bacteria enhance this decomposition (Gray and Williams 1971).

The rate at which proteolysis proceeds depends largely on moisture, temperature and bacterial action. In general terms, the proteins break down into proteoses, peptones, polypeptides and amino acids. Continuing proteolysis leads to the production of the phenolic substances skatole and indole, and the evolution of gases such as carbon dioxide, hydrogen sulfide, ammonia and methane (Evans 1963; Fig. 3). The common proteolytic bacteria genera are: *Pseudomonas, Bacillus* and *Micrococcus* (Higgins and Burns 1975).

The sulfur containing amino acids of the proteins, for example cysteine, cystine, and the essential methionine (Hart and Schuetz 1966; Gill-King 1999), undergo desulfhydralation and decomposition by the action of bacteria to yield hydrogen sulfide gas, sulfides, ammonia, thiols and pyruvic acid. In the presence of iron, hydrogen sulfide will produce the familiar black precipitate, ferrous sulfide, often associated with decomposing remains. The anaerobic conditions of the grave favour sulfide production in considerable quantities (Waksman and Starkey 1931).

Thiols or mercaptans are decomposition gases containing the –SH (sulfhydryl group). They are notable for their disagreeable odour. They are acidic and form insoluble solutions with heavy metals, for example mercury. Many thiols form from aromatic molecules and are often eventually converted to disulfides (Hart and Schuetz 1966; Alexander 1999). The term 'mercaptans', although common in discussions of landfills, is very infrequently used in the context of cemeteries. Two prominent decarboxylation products of proteins include the gases putrescine (derived from Ornithine) and cadaverine (derived from Lysine) (Gill-King 1999). Both are highly toxic and have a foul odour (part of a well-known group of diamines) and

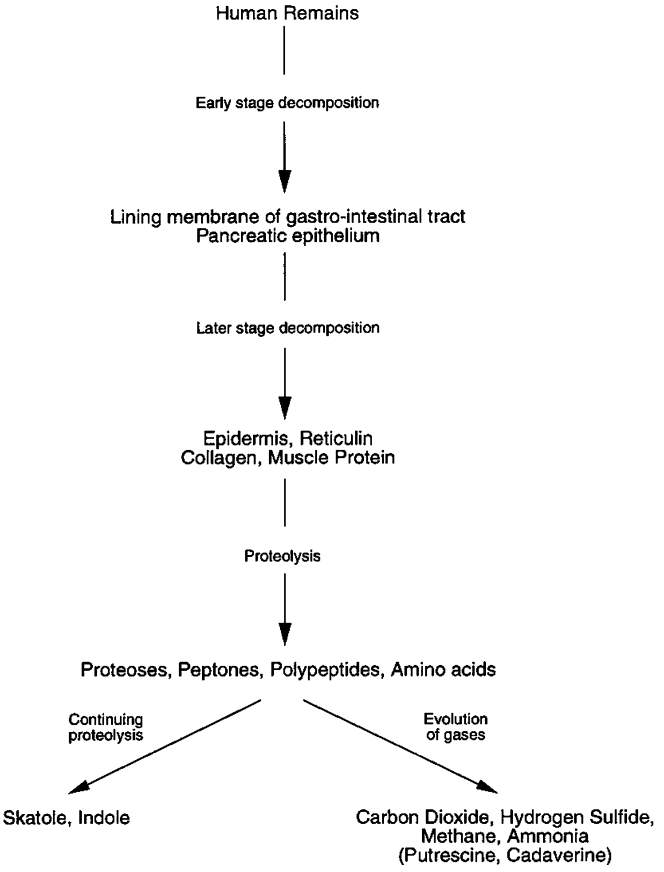

Fig. 3
Changes to protein during decomposition

together with hydrogen sulfide and methane, are usually present in soils where bodies may be decomposing.

The decomposition processes result in the production of a range of organic acids and other substances that become bacterial metabolites. These are generally of low or moderate molecular weight, anionic or non-ionic, and are susceptible to rapid breakdown by bacteria (Santoro and Stotzky 1968). These compounds may produce several effects that might be observable in cemetery vadose zones or water table aquifers; including alterations of pH or providing a nutrient source for bacteria along groundwater pathways. In addition, they may have an effect on altering electrokinetic potentials of clays so that bacteria are assisted in being adsorbed to them (Santoro and Stotzky 1968). This latter idea, wherein bacteria to clay adsorption is mostly explained in terms of the nature of the charged surfaces of the clay itself or of the bacteria, has not been developed significantly in the literature.

Under anaerobic conditions, any sulfide product is not transformed further. However, under aerobic conditions it soon disappears and is oxidized to elementary sulfur and then rapidly to sulfate through a series of steps producing sulfurous acids which are variously detectable in groundwater. This process is in common with standard chemical weathering of sediments. Various specific bacteria, mainly belonging to the *Thiobacillus* group, are also capable of bringing about these processes in the soil.

The nitrogen of proteins is present as a constituent of amino acids. The amino acids are readily used by most of the soil microbes as a source of energy when the proteins undergo deamination, for example Phenylpyruvic acid derives form L-phenylalanine (Gill-King 1999). The nitrogen, however, is liberated by chemical reactions as ammonia. The ammonia produced may in turn be used by higher plants or various microbes, may be converted to nitrate, may accumulate in the soil or move through the groundwater system (Waksman and Starkey 1931).
Gill-King (1999) has suggested that plant growth may sometimes be enhanced nearby to decomposing, shallowly buried remains.
In the presence of low soil pH, ammonia (NH_3) is converted to ammonium ions ($NH_3+H^+ \rightarrow NH_4^+$), which are readily utilized by plants. Under alkaline conditions, a fraction of the ammonium ions entering the soil may revert to ammonia and undergo volatilization ($NH_4^+ \rightarrow NH_3$). Furthermore, ammonium ions may become incorporated into microbial tissue, thus re-entering living organisms. Alternatively, ammonium ions not intercepted through one of the above mechanisms can undergo nitrification and denitrification. Nitrification can occur directly (by light) or during the metabolism of some heterotrophs (Gray and Williams 1971), but is more usually accomplished by various species of soil organisms that convert ammonia to nitrate. Two autotrophic bacteria are the most important: the first oxidizes ammonia to nitrite (*Nitrosomonas* spp.), and the second transforms nitrite to nitrate (*Nitrobacter* spp.) (Waksman and Starkey 1931). None of the bacteria belonging to either group is capable of transforming ammonia directly to nitrate; each is confined to merely one stage of the reaction. There are also other, less widely known, nitrifying bacteria—*Nitrosococcus* spp., *Nitrosocystis* spp., and *Nitrospir* spp. (Gray and Williams 1971) whose roles are not fully established.
The conditions suitable for the formation of nitrite and nitrate by nitrifying bacteria (i.e. nitrification) include an inorganic medium containing salts of ammonia, aerobic conditions and a neutral reaction. The nitrifying organisms, however, unlike the denitrifiers are very sensitive to environmental pH. *Nitrobacter* spp., prefer a pH between 5 and 8, while *Nitrosomas* species have optimum conditions at pH 7 to 9. In the right medium, transformation of ammonia gives rise to nitrite, and once a large part of the ammonia has disappeared, nitrate is then formed. Nitrification normally occurs above the water table in the soil zone where organic matter and oxygen are abundant; the reactions are inhibited by high pH or added lime, and stop altogether at pH less than 5 (Gray and Williams 1971; Higgins and Burns 1975; Bolt and Bruggenwert 1978).
Denitrification refers to the reduction of nitrate to nitrite, gaseous nitrogen or nitrous oxide. The conditions necessary for denitrification (ammonification) to occur include a prevalence of nitrate, an energy source and anaerobic conditions. The organisms known to be denitrifiers include *Achromobacter* spp., *Bacillus* spp., *Micrococcus* spp. and *Pseudomonas* spp. (Bolt and Bruggenwert 1978) but not *Pseudomonas aeruginosa*. This last bacterium is important as a waterborne pathogen and is further considered later.
The remaining ammonium ions that do not undergo any of the above processes will be displaced through the soil subject to several types of adsorption and fixation processes. These processes include regular cation exchange, intra-lattice fixation and direct adsorption by organic matter. In this way, ammonium ions may leach to deeper layers and eventually reach the groundwater.
When nitrifying bacteria or organisms capable of oxidizing ammonia are absent, the ammonia will accumulate in the soil.
Many kinds of anaerobic bacteria are able to split off ammonia from amino acids thus producing large amounts of ammonia in oxygen deficient areas. Furthermore, while ammonia can be oxidized to nitrate under aerobic conditions, nitrification is completely inhibited under anaerobic conditions, causing a greater accumulation of ammonia in anaerobic environments than where there is freer access of oxygen. Denitrification is inhibited in the presence of oxygen. Waterlogged soils experience the highest denitrification rates.
In cemetery groundwaters it would be expected that ammonium concentration decreases with distance from graves, or as groundwater moves from newer to older interment areas. Conversely, nitrite and more particularly nitrate should increase in these circumstances. In clayey soils, ammonia would be expected to denitrify to nitrogen gas and nitrous oxide accompanied by higher amounts of ammonium and low nitrate concentrations: suggesting that lower total nitrogen would be observed compared to the situation in more permeable soils.
Phosphorus is another important element that should also be considered. In the body the phosphorus store is found in a number of components: in proteins comprising nucleic acids and coenzymes; in sugar phosphate; and in phospholipids (fats) of the brain and spinal cord. As phosphorus is liberated during decomposition it does not follow simple pathways nor does it remain in elemental form.
The mobility of phosphorus is far from simple. Phosphorus leaching in its oxidized forms—orthophosphates, appears to be tightly controlled by slight soil acidity within the range pH 6–7, yet these forms are the most thermodynamically stable and hence most mobile (Hem 1989). Above pH 7 and certainly below pH 5 the phosphorus is locked up into insoluble components (Cook and Heizer 1965; Reimann and de Caritat 1998). In most soils, the phosphorus is likely to exist as insoluble inorganic complexes, probably associated with iron, calcium, magnesium and aluminum (Higgins and Burns 1975); this is especially likely for grave soils. Consequently, little leached phosphorus is expected in cemetery groundwaters in a general sense, but it will be very dependent on the hydrogeological context. The situation may be complicated by addition of lawn and garden fertilizers containing phosphates.
Soil microorganisms also play a role in phosphorus transformations from insoluble organic complexes to soluble ones and its release from mineral forms as well as its incorporation in new protoplasm. "A great many microbes (*Pseudomonas, Mycobacterium, Micrococcus, Flavobacterium, Penicillium, Aspergillus* and others) have the ability to solubilize inorganic phosphorus compounds" (Higgins

and Burns 1975). The common process of adsorption of phosphorus by metal oxides—notably those of iron and manganese, might also imply that any released phosphorus may be continuously recycled within parts of some cemeteries with suitable environments; and/or there may be a net migration off-site.

Phosphorus derived from body decomposition has had an interesting association with evidence of burial. This is the phenomenon of burial silhouettes/pseudomorphs wherein the former body is outlined with a dark stain/deposits at the level of interment. It has been suggested that in sandy and gravelly, acidic conditions that the organic phosphorus complexes further attract soil metals, notably manganese, to make the dark stains. The phenomenon is still not fully explained but has been well considered for inhumations at Sutton Hoo, UK (Bethell and Carver 1987). Interestingly, the phenomenon has also been noted in a tropical setting—Tonga (Spennemann and Franke 1994), but the chemistry was incompletely considered in this example.

Decomposition products of fat

The body's adipose tissue typically comprises, by weight, 5–30% water, 2–3% proteins and 60–85% lipids (fats), of which 90–99% are triglycerides (Reynold and Cahill 1965). Triglycerides are composed of one glycerol molecule attached to three fatty acid molecules. Of the numerous fatty acids that may be attached, monounsaturated oleic acid is the most widespread in adipose tissue followed by linoleic, palmitoleic, (both unsaturated) and palmitic (saturated) acids.

The neutral fat of decomposing remains can undergo hydrolysis to yield fatty acids, which may subsequently undergo either hydrogenation or oxidation. Neutral fat is hydrolyzed by intrinsic tissue lipases shortly after death to produce a mixture of saturated and unsaturated fatty acids. Hydrogenation of oleic, linoleic and palmitoleic acids yields stearic, oleic and palmitic acids, respectively. More extensive hydrolysis and hydrogenation increases the mixture of saturated fatty acids while decreasing the relative amount of unsaturated fatty acids (Evans 1963). Hydroxy-fatty acids may also be formed at this stage in small amounts (Fig. 4).

Providing there is sufficient water and enzymes available the process will continue until no neutral fat remains and the original adipose tissue is reduced to a mass of fatty acids which under the right conditions yield adipocere. These fatty acids can react with sodium and potassium ions present in tissue fluids at neutral or slightly alkaline intracellular pH to form salts of fatty acids. Once the body is deposited in a grave the sodium and potassium may be displaced by calcium or magnesium ions present in the soil (Gill-King 1999; Forbes 2003). The result is the formation of water insoluble soaps of the saturated fatty acids that are known to comprise adipocere.

The fatty acids can also undergo oxidation by the action of bacteria, fungi and atmospheric oxygen. Oxidation occurs under aerobic conditions and the exposure of fatty tissues to visible and ultraviolet light will accelerate their breakdown. If the neutral fat has been hydrolyzed to produce a large concentration of unsaturated fatty acids, oxidation of these fatty acids can thus result in the production of aldehydes and ketones (Evans 1963).

Within a closed coffin, oxidative changes are less likely than hydrolytic changes because the human remains are being continuously exposed to the reducing conditions. These conditions will slow and eventually halt the oxidative process. If the burial conditions keep the oxygen levels low then the fat degradation products will remain as adipocere (Mant 1957; Henderson 1987). The intrinsic bacterium *Clostridium perfringens (welchii),* which derives from the intestine, produces a powerful enzyme, which significantly aids the anaerobic hydrolysis and hydrogenation of the fat under warm conditions (Corry 1978; Polson and others 1985).

Both hydrolytic and oxidative processes generated by various fungi and bacteria will continue to decompose the adipose tissue in the soil. The glycerol and fatty acids breakdown giving shorter-chain saturated fatty acids and eventually carbon dioxide and water. However, little is known about which specific microorganisms bring about lipid breakdown in soil (Gray and Williams 1971; Cabriol and others 1998). In Brazilian cemetery studies the presence of significant numbers, but unspecified types of lipolytic bacteria (possibly *Clostridia* spp.), was reported for the groundwaters examined (Martins and others 1991); these were said to be directly related to the decomposition of the interred remains.

The bacterium *Clostridium perfringens* has been widely implicated as a major agent for anaerobic decomposition of cadavers because it is a resident of the human intestine and has strong saccharolytic, proteolytic and lipolytic capabilities as well as being able to grow at a relatively high redox potential (Eh, Corry 1978). While it is doubtlessly important, its reproduction and activity is very limited to favourable environmental conditions—mainly warm temperature. These optimum conditions are 15 to 45 °C (Corry 1978); furthermore, *Cl. perfringens* is a common inhabitant of soils (Lewis-Jones and Winkler 1991; World Health Organisation (WHO) 1993) so that its participation in decomposition may in fact derive from the surroundings as well. The *Clostridium* genus is a ubiquitous inhabitant of soils (Haagsma 1991).

Decomposition products of carbohydrate

The carbohydrates in the soft tissues also break down during the decomposition process. For example glycogen, a complex polysaccharide, will break down into sugars (glucose monomers) by the action of microorganisms. This destruction occurs in the early stages of decomposition and is evidenced largely in the liver (Evans 1963). Some of the sugars are completely oxidized to

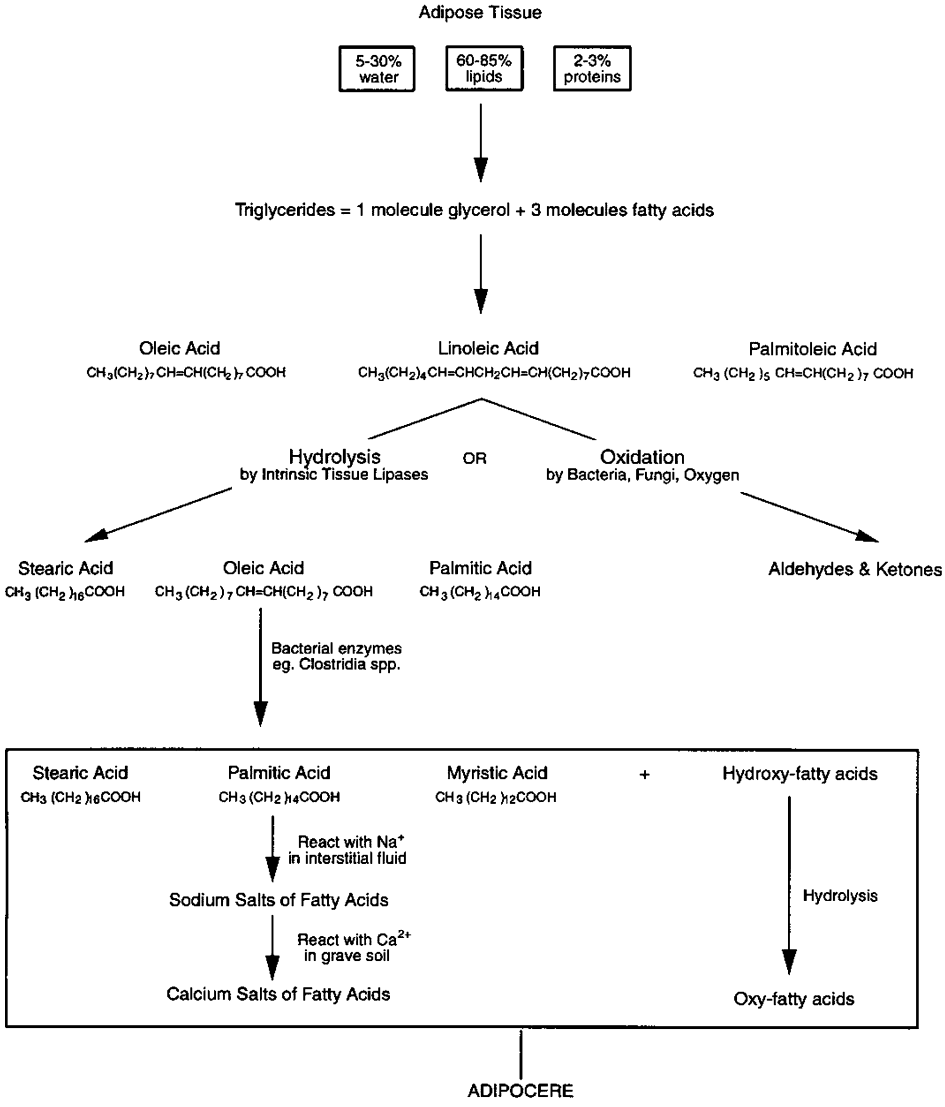

Fig. 4
Changes to fat during decomposition

carbon dioxide and water while some are incompletely decomposed for example by *Clostridia* spp. to form a number of organic acids and alcohols.

Fungi decompose the sugars to form organic acids including glucuronic acid, citric acid and oxalic acid (Waksman and Starkey 1931). Bacteria decompose sugars in a different manner to fungi and the resulting end products are determined principally by the presence or absence of free oxygen in the organisms' environments. Under anaerobic conditions, lactic acid, butyric acid and acetic acid are produced as well as alcohols including butyl alcohol, ethyl alcohol and acetone. In the presence of oxygen, the glucose monomer is broken down through the pyruvic acid, lactic acid and acetaldehyde stages to form carbon dioxide and water (Waksman and Starkey 1931). Other gases produced through bacterial carbohydrate fermentation include methane, hydrogen and hydrogen sulfide (Fig. 5).

The comprehensive understanding of organic decomposition products of the cemetery needs to also take into account natural processes. A number of studies of rocks and soils report native carbohydrate components. In the case of soils, carbohydrates as polysaccharides generated by microbial action to decompose vegetative material are found in the deeper subsoils. Whereas in the upper soil horizons monosaccharides predominate and can comprise from 9–24% (Folsom and others 1974) of the total organic carbon fraction. In the cemetery situation, where there is a mixing of soils as a consequence of grave excavation and refilling processes, some small variation to the carbohydrate loading could be induced. This is then likely to be further decomposed anaerobically.

In another study, Whitelaw and Edwards (1980) reported the presence of natural carbohydrates in the chalks of England. The implications of this work also have a minor consequence for the understanding of cemetery processes because their results indicated that the natural carbohydrate content affected pore-water nitrate concentrations in the unsaturated zone. That is, the mere presence of carbohydrate in the grave environment (natural and interred), and its support for nitrate-reducing and ammonia-oxidizing bacteria, is likely to lead to the alteration of forms of inorganic nitrogen leaving the gravesite. Most probably there will be an additional loss as nitrogen gas,

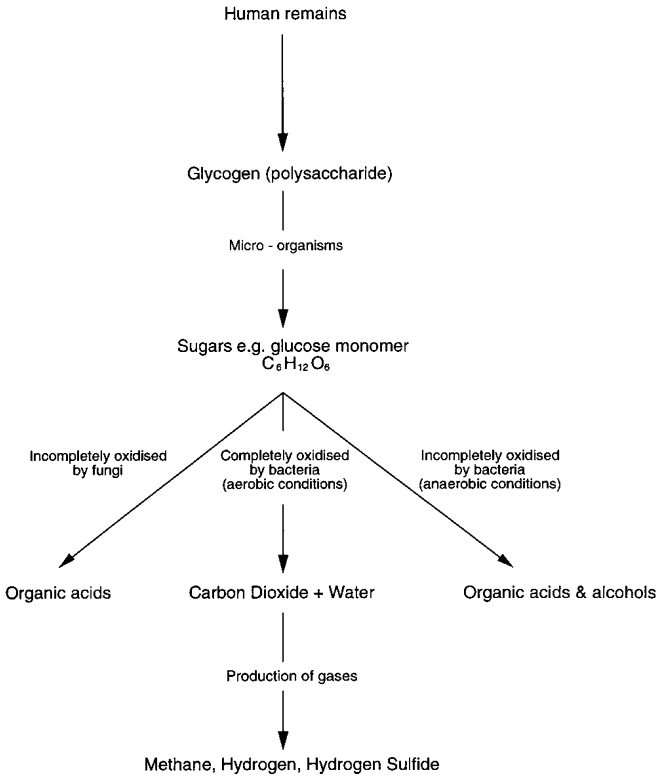

Fig. 5
Changes to carbohydrate during decomposition

thus influencing any stoichiometric calculation of nitrogenous oxides or ammonia groundwater products.

Liquefaction

The body's tissues and organs soften during decomposition and degenerate to a mass of unrecognizable tissue that under continued decomposition becomes liquefied. This liquefaction is aided by the breakdown of proteins to simpler units thus allowing a greater range of microorganisms to grow on the substrate and to subsequently be dispersed throughout the tissues. Discoloured natural liquids and liquefying tissues are made frothy by the gases forming within the decomposing remains. Some of these liquefaction products may exude from the natural orifices, forced out by the increasing pressure of the gases (Janaway 1997).

Much folklore surrounds the occurrence of gaseous decomposition products and their effects on coffins—mostly concerning explosive disintegration of the coffins at sometime during their storage. The issue is discussed in detail by Lewis (1851) and also reported on by Evans (1963), Polson and others (1985) and Wilkins (1992). The occurrence of any such phenomenon is rare, and only in a few cases has gaseous bulging been detected or gas composition measured.

In the case of a body buried directly in the soil, a mucus sheath will form around the corpse consisting of liquid body decomposition products and the 'fines' soil fraction (Janaway 1997). Coffin burials, on the other hand, often produce a semi-fluid mass consisting of water and putrefied tissue with a powerful ammoniacal odour. This mass is only retained in sealed coffins.

The recordings of various researchers who have studied mass exhumations of sealed coffins, mostly in the UK, report on occasions that these coffins contain soft tissue and liquor; but the reports are infrequent. It appears that "sealed" coffins are eventually breached by either mechanical stress during storage or chemical reactions from within or without (Lewis 1851; Evans 1963; Goffer 1980; Polson and others 1985; Janaway 1993). Consequently it is more common to find skeletonized remains with extensive adipocere formation; often burial and funereal artifacts and textiles are quite intact (Janaway 1993).

Ultimately, liquefaction and disintegration of the soft tissues leave behind skeletonized remains. At this stage the skeletonized body will be held together by ligaments and surrounded by a putrescent or liquefying mass. Eventually the liquefaction products will be incorporated within percolating water and enter surrounding soil and groundwater systems.

Decomposition products of bone

Skeletonization refers to the removal of soft tissue from bone. The process is considered 'complete' if all soft tissue is removed and 'partial' if only portions of the bone are exposed. Under appropriate conditions, a partially skeletonized body can proceed to complete skeletonization. The rate at which skeletonization proceeds depends on depth of burial, soil type and surrounding environment (Mann and others 1989; Clark and others 1997). For example, a body buried in a warm environment may skeletonize as quickly as an exposed body in a mild environment. The arresting effects of a cold or dry burial environment on decomposition are well known and documented (Polson and others 1985; Janaway 1997), so that in some instances skeletonization can take a very long time. This matter is consequential for the future of cemeteries in today's cold and/or dry climatic zones: when climate changes occur the ground condition will vary and decomposition rates will increase. These phenomena will be attended by the release of decomposition products.

Skin, muscle and internal organs are generally lost to the environment well before a skeleton becomes disarticulated. Bone is broken down over time by physical breaking, decalcification, and dissolution due to acidic soil or water. Bodies which are not buried in tombs or coffins may disappear completely, or under the right conditions may become fossilized and preserved for thousands of years (Clark and others 1997; Galloway 1997).

Bone is a composite tissue and is composed of three main fractions: a protein fraction consisting mainly of collagen which acts as a supportive scaffold; a mineral component consisting of hydroxyapatite to stiffen the

protein structure; and a ground substance of other organic compounds such as mucopolysaccharides and glycoproteins (Hare 1976; Goffer 1980; Janaway 1997). The collagen and hydroxyapatite are strongly held together by a protein-mineral bond that gives bone its strength and contributes to its preservation.

The organic collagen phase of bone is eliminated predominantly by the action of bacterial collagenases by reducing the proteins to peptides, which in turn break down to their constituent amino acids and leach away in groundwater. Collagen degradation is also thought to be affected by the activity of the gas-gangrene bacteria (*Clostridium* spp.) that operate in a pH range of 7–8 (Janaway 1997).

Following elimination of the collagen phase, the loss of mineral hydroxyapatite proceeds by inorganic mineral weathering. The calcium ions in the apatite crystal migrate into the soil solution when they are replaced by protons at low pH. Not only is there removal of proteins and minerals but also substitution, infiltration and adsorption of ions, which serve to undermine the protein-mineral bond leaving the bone susceptible to internal and external elements.

Bone preservation in all manner of physical condition is dependent on the burial environment. Bone excavated from aerobic, non-acidic environments often appears to be in good condition but demonstrates surface coarsening in fine sands and further cracking may occur upon drying. In calcareous sand or loam where it is damp and there is more oxygen present, the bone surface will be rougher and may crack, warp or laminate upon drying. Bone buried in coarse calcareous gravels will lose large amounts of collagen and have the consistency of powdery chalk, while bone from acidic peat deposits is pliable and will harden on drying. Acidic soils are the most destructive as they work by dissolving the inorganic matrix of hydroxyapatite which produces an organic material susceptible to leaching by water (Goffer 1980; Henderson 1987).

In general, bone preservation is best in soils with a neutral or slightly alkaline pH, and is worse in acid conditions. Dry sand assists preservation because of reduced bacterial action yet elsewhere sandy and permeable soils assist decomposition because of the free exchange of water and gases (Hare 1976; Janaway 1997).

During life, the body's bones accumulate trace amounts of non-primary elements—notably strontium and fluorine (Goffer 1980) and various metals, so that these are available to be released during the later chemical weathering of decomposition. The issue of bone chemistry and it sorption and desorption of metals in soils is quite debatable and has been the subject of a very large number of studies.

Other in-grave processes

Most interments in 'westernized' cemeteries have the remains contained within coffins made of timber or wood products with or without metal as a lining or covering; or else they may be entirely comprised of metal/metals which have in the past typically included lead.

The wood products are also subject to in-soil decomposition processes. The plant materials comprising the coffin include forms of one or more of cellulose, hemicellulose and lignin. The decomposition of these materials into their primary constituents and their incorporation in the soil matrix is now well understood. However, this understanding has been largely limited to studies focused on the immediate surface and shallow layers of the regolith (to about 1 m), which may have some, as yet unknown, implications for the processes at the usually greater depths of interments. A suitable explanation of soil ecological relationships and the breakdown pathways, for the present, is given in Killman (1994). Some of the mechanisms and pathways involved in plant decomposition, for example the generation of organic acids, the dealing with inorganic N, and sulfur oxidation, are analogous to those for human decomposition.

Summary

The understanding of in-soil human decomposition processes needs to take into account the knowledge of soil environmental factors and details of the remains' interment. It is not sufficient to assume that aerobic or anaerobic, acid or alkaline conditions will always produce the same outcomes. The decomposition processes are primarily affected by the nature of the remains, the nature of the site, the infiltration and percolation of groundwater and atmospheric gases, the exhalation or percolation of decomposition gases, the climate, encapsulation of the remains, native soil flora and fauna, the physical aspects of the interment process, and of course, time.

Consequent on the interplay of these factors, some of which are likely to have only a minor role at times, the development, presence of, and/or migration of, any single decomposition product will vary from site to site. This has implications for considerations of environmental loadings imposed by cemeteries and interpretation of forensic sites. Given sufficient time for the prevailing environmental conditions so that skeletonization is complete, then inorganic chemical weathering processes and percolation of groundwater provide the sustaining effects.

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