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Oxidative degradation of fragrant aldehydes. Autoxidation by molecular oxygen

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ABSTRACT

The oxidative degradation of fragrant aldehydes by molecular oxygen has been investigated. The oxygen consumption was monitored and the bond dissociation energy (BDE) of the aldehyde C(O)–H bond were calculated by DFT method. The oxidation products were identified by GC/MS. The different pathways accounting for the oxidative degradation are discussed. The main product is the acid, beside the formate ester. Both oxidation products result from the Baeyer–Villiger reaction involving a peracid R(CO)OOH whereas minor products arise from the hydroperoxide ROOH intermediate derived either from the acyl peroxy radical, R(CO)OO• or from the decarboxylation of the peracid RC(O)OOH.

1. Introduction

Oxidative degradation of organic compounds, involving either ground state molecular dioxygen ($^3O_2$) or reactive oxygen species (ROS), such as singlet oxygen $^1O_2$, superoxide anion $O_2^{\bullet -}$, hydro (pero)xyl HO• and HOO•, alkoxy RO•, peroxy ROO•, acyl RCO• and acyl peroxy RC(O)OO• radicals, is an important issue to account for the long-term stability of many end-use products.[1] For perfume suppliers and the cosmetic industry in particular, the oxidation of fragrance molecules is directly linked to the product safety, shelf-life, off notes or colouration, which must be avoided. Moreover, during the last 20 years, fragrance contact allergy has also become a major problem due to an increase of fragrance-based products and because the products resulting from the oxidative degradation of fragrances, such as hydroperoxides are frequent causes of contact allergy.[2] Studies have proven that almost 1% of the population suffers from respiratory threats caused by allergens in perfumes and fragrances.[3] This has led to a list of 26 fragrance molecules, which have to be mentioned on the packaging since 1999 when they are present in a formulation. For these reasons, it appears crucial to understand the mechanisms involved and responsible for the formation of allergens, which have to be clearly identified. From several years, the mechanism of air oxidation of some typical fragrance molecules, in particular terpenes and terpenoids, such as limonene, geraniol, linalool, caryophyllene, have been thoroughly investigated with a special focus at their skin sensitizing properties through the formation of hydroperoxides.[4]

Fragrance molecules, typically terpenes and phenols but also aldehydes, are actually electron-rich molecules likely to oxidize readily upon contact air exposure.[5] Their oxidation, occurring through a free radical chain process, can be initiated by several external factors like heat, oxygen, light but also by impurities often present in perfumes like traces of metals, hydroperoxides, peracids, photosensitizers, etc. as well as by interaction with the other ingredients of the formulation, such as enzymes or bleaching agents.[6] Preventing a complex mixture of fragrances from oxidation in order to minimize the presence of unfavourable by-products is a real challenge, which has become nowadays a priority for the perfumer who must take care to maintain both the safety and the performances of the product. Among the diversity of fragrance molecules, aldehydes are the most sensitive towards oxidation by $^3O_2$ since the bond dissociation energy (BDE) of the aldehyde function is relatively low ($\approx$89 kcal mol^{-1}) leading to a radical RC(O)• through hydrogen abstraction.[7] Aldehydes are present in many fragrance compositions. As an example, 2-methylundecanal was the first synthetic aldehyde molecule introduced into a perfume in 1921, i.e., the famous Chanel n°5. However, their degradation takes place rapidly involving

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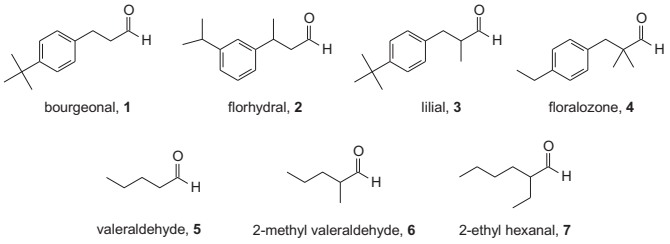
different types of radical species.[8] From a general view point, the reaction occurs through classical radical pathways already described for current aldehydes but very little work report studies dealing with fragrant aldehydes specifically used in perfumery.[9]

In the present work, we have investigated the oxidation of seven fragrant aldehydes commonly used in fine perfumery. As a kinetic approach, the oxidation rates have been determined by monitoring the oxygen consumption. Bond dissociation energies (BDE) have also been calculated in order to rationalize the oxidability of the fragrant aldehydes. In a second step, the oxidation products have been detected and identified by GC/MS. Combination of all this information led us to propose a complete mechanism for the autoxidation as well as a rationalization of the structural effects on the autoxidation of fragrant aldehydes.

2. Results and discussion

From a general point of view, oxidation of aldehydes by ground state dioxygen ($^3O_2$) is known for a long time.[11] As early as 1835, Liebig observed that in the presence of air, aldehydes are converted into their corresponding acids.[12] Since that time, the reaction has been widely studied with various aldehydes and the detailed mechanism is now well established.[12] Surprisingly, very little work report studies dealing with fragrant aldehydes specifically used in perfumery in spite of the importance of this phenomenon for the stability of fragrance composition and for consumer health.[9] The autoxidation of seven fragrant aldehyde molecules, selected for their structural features and their interest in perfumery (Scheme 1) has thus been investigated. Except valeraldehyde **5**, they all bear either alkyl or benzyl substituents in α position of the aldehyde function in order to study the impact of substitution on their oxidability.



Scheme 1. Chemical structures of the fragrant aldehydes.

2.1. Kinetic and thermodynamic approaches of the autoxidation of fragrant aldehydes

The autoxidation of aldehydes RCHO **8** is well known for a long time. It occurs through a free radical chain process involving a series of elementary reactions, i.e., initiation, propagation and termination steps. As reported by many authors, initiation starts with abstraction of the aldehydic hydrogen, induced by (i) heat plus O_2 (reactions 1a and 1b), (ii) transition metallic ions traces, (iii) UV light or (iv) traces of peroxides present in the medium.[12,13] All these various initiation reactions are represented through the generic Eq. 1 that leads to the formation of acyl radicals R(CO)$^\bullet$ according to a global initiation rate constant R_i.

Initiation

$$\mathrm{RCHO} \xrightarrow{\mathrm{Ri}} \mathrm{R(CO)^\bullet} \quad (1)$$

$$\mathrm{RCHO + O_2 \rightarrow R(CO)^\bullet + HOO^\bullet} \quad (1a)$$

$$\mathrm{2RCHO + O_2 \rightarrow 2R(CO)^\bullet + H_2O_2} \quad (1b)$$

$$\mathrm{RCHO + ROOH \rightarrow R(CO)^\bullet + RO^\bullet + H_2O} \quad (1c)$$

Denisov has shown that, in peroxide-free aldehydes, the trimolecular reaction 1b predominates when the aldehyde exhibits a very low BDE of the C(O)–H bond, such as benzaldehyde and unsaturated aldehydes whereas in other cases, the bimolecular reaction 1a is usually the main pathway.[7] However, according to Peeters et al., the other pathway 1c might be important in the presence of traces of peroxide since they reported that the dissociation of peroxides can be accelerated by the abstraction of the weak H-atom of the aldehyde group.[14]

Propagation

$$\mathrm{RCO^\bullet + {}^3O_2 \rightarrow R(CO)OO^\bullet} \quad (2)$$

$$\mathrm{R(CO)OO^\bullet + RCHO \xrightarrow{k_p} R(CO)OOH + R(CO)^\bullet} \quad (3)$$

Termination

$$\mathrm{2R(CO)OO^\bullet \xrightarrow{k_t} \text{molecular products}} \quad (4)$$

During the propagation step, the acyl radical R(CO)$^\bullet$ rapidly reacts with an oxygen molecule to give the acyl peroxy radical R(CO)OO$^\bullet$ (Eq. 2), which abstracts a hydrogen atom to another aldehyde molecule with a relatively high rate constant k_p ($\approx 10^3$ mol L^{-1} s^{-1}) compared to $\approx$1–10 mol L^{-1} s^{-1} for alkyl peroxy radicals on alkene,[8] giving the corresponding peracid R(CO)OOH and regenerating at the same time the acyl radical R(CO)$^\bullet$ (Eq. 3). In the termination step, the acyl peroxy radical R(CO)OO$^\bullet$ can recombine leading to the acyloxy radical R(CO)O$^\bullet$ as an intermediate, which gives, after decarboxylation and oxygen addition, minor oxidation products, such as alcohols, aldehydes or ketones (Eq. 4) (see Section 2.3 for details and discussion). However, the main pathway providing the major oxidation products, i.e., the carboxylic acids **11** and the formate esters **12**, corresponds to the addition of the peracid R(CO)OOH on the starting aldehyde according to the Baeyer–Villiger rearrangement (Eq. 5). Besides the acid, an ester formate can also be formed (Eq. 6).[15]

Non-radical molecular reactions

$$\mathrm{R(CO)OOH + RCHO \rightarrow 2RCOOH} \quad (5)$$

$$\mathrm{R(CO)OOH + RCHO \rightarrow RCOOH + ROCHO} \quad (6)$$

The determination of the propagation rate constant (k_p) (Eq. 3) can be used to discuss the oxidability of organic compounds (RH) since it is generally well correlated to the activation energy of the hydrogen atom transfer reaction.[16] k_p is determined by measuring the rate of oxygen consumption ($-d[O_2]/dt$) knowing the rate constants of the termination (k_t) and of the initiation rate (R_i) according to Eq. 7.[17]

$$-\frac{\mathrm{d}[O_2]}{\mathrm{d}t} = \frac{R_i^{0.5}[\mathrm{RH}]k_p}{\sqrt{2k_t}} \quad (7)$$

Since rate constants of the termination and initiation steps for the fragrant aldehydes are not referenced, k_p cannot be easily determined. Hence, $-d[O_2]/dt$ determined using the PetroOxy apparatus can be used as an indicator of the oxidability since generally, the ratio $k_p/(2k_t)^{0.5}$ is used as an oxidability parameter.[18] The seven fragrant aldehydes have thus been oxidized at a concentration