ELSEVIER

International Dairy Journal 12 (2002) 959–984

INTERNATIONAL DAIRY JOURNAL

www.elsevier.com/locate/idairyj

Review

Key odorants in various cheese types as determined by gas chromatography-olfactometry

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Received 13 June 2002; accepted 7 August 2002

Abstract

Cheese odour-active compounds identified by gas chromatography-olfactometry (GC-O) are compiled in nine tables dealing with alcohols, aldehydes, ketones, esters, lactones, furans, nitrogen-containing compounds together with pyrazines and sulphur-containing compounds, terpenes and miscellaneous compounds, and, finally, aromatic compounds and free fatty acids. For each component, the odour descriptors, the cheese variety in which it was evaluated, the concentration (or an indication of the odour intensity), the extraction method, the GC-O type of analysis, and, if available, the perception threshold values are also provided. The sensory properties and metabolic origin of major cheese aroma compounds are discussed in the text, explaining to a certain extent the discrepancies between different authors.

Keywords: Cheese; Gas chromatography-olfactometry (GC-O); Aroma compound; Odorant

Contents

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0958-6946/02/$ - see front matter
PII: S0958-6946(02)00124-3

1. Introduction

Volatile (aroma) components of various dairy products have received a great deal of attention. So far, more than 600 volatile compounds have been identified in cheese (Maarse & Visscher, 1989). However, there is a general agreement that only a small fraction of these compounds are really responsible for cheese flavour. In many cases, the most abundant volatiles may have little, if any, odour significance in dairy products. This leads to great confusion in the literature between odour-active compounds and those which are insignificant. Such distinction should become a challenge to flavour chemists in the future.

Many studies have used gas chromatography, coupled with mass spectroscopy (GC-MS), to analyse the aroma of dairy products and several reviews have been published on this topic (Badings & Neeter, 1980; Gallois & Langlois, 1990; Engels, Dekker, de Jong, Neeter, & Visser, 1997; Sablé & Cottenceau, 1999; Lawlor, Delahunty, Wilkinson, & Sheehan, 2001). However, GC-MS is a useful method for identifying and quantifying flavour substances, but it does not allow to establish whether such compounds are odour-active or not. In complement, gas chromatography-olfactometry (GC-O) provides a valuable tool for investigating the pattern of odorants in terms of both their odour descriptors and activity. GC-O can be defined as a collection of techniques that combine olfactometry, or the use of the human nose as a detector, to access odour activity in defined air streams, with the very popular gas chromatographic separation of volatiles (Friedich & Acree, 1998). Theoretically, the human nose can have a detection limit down to 10^{-19} moles for certain odours (Reineccius, 1994). Therefore, it can be successfully used for the analysis of chromatographic effluents and in many cases is much more sensitive than an instrumental detector such as a flame ionisation detector.

Several techniques have been proposed for the extraction, isolation and gas chromatographic injection of volatile components of dairy products (Bosset & Gauch, 1993; Mariaca & Bosset, 1997; Deibler, Acree, & Lavin, 1999). These procedures can be divided into five main groups: (i) direct extraction methods by which an organic extract is obtained by liquid–liquid or liquid–solid partitioning; (ii) supercritical fluid extraction (SFE) methods using CO_2; (iii) steam distillation or "stripping" methods that produce large quantities of aqueous extracts which then have to be concentrated in a further step by liquid–liquid partitioning or by cryoconcentration; (iv) high-vacuum (or molecular) distillation methods, which are, in principle, variants of the previous group but work under higher vacuum and lower temperature; (v) static, as well as dynamic, headspace techniques in which the analysed sample is an aliquot of the gas-phase containing the volatile components released by the food.

The data that are generated by subsequent GC-O analysis can be evaluated using the following types of analysis: (i) Aroma Extract Dilution Analysis (AEDA) (Ullrich & Grosch, 1987; Grosch, 1994); (ii) Aroma Extract Concentration Analysis (AECA) (Kerscher & Grosch, 1997); (iii) CharmAnalysis™ (Combined Hedonic Aroma Response Measurement) (Acree & Barnard, 1984; Acree, Barnard, & Cunningham, 1984); (iv) Osme (from the Greek word meaning "odour") (McDaniel, Miranda-Lopez, Watson, Michaels, & Libbey, 1990; Miranda-Lopez, Libbey, Watson, & McDaniel, 1992); (v) Nasal Impact Frequency (NIF) and Surface of Nasal Impact Frequency (SNIF) analyses by using a panel of trained persons to do the sniffing (Pollien et al., 1997).

So far, a comprehensive list of cheese key odorants, determined by GC-O, has not been established. Thus, the aim of the present paper is to summarise the current knowledge on this topic and compile key odour compounds determined in various cheese varieties using different extraction procedures and GC-O methods.

2. Neutral compounds

2.1. Alcohols

Many metabolic pathways are involved in the biosynthesis of the alcohols (Table 1) that are encountered in cheese: lactose metabolism, methyl ketone reduction, amino acid metabolism as well as degradation of linoleic and linolenic acids (Molimard & Spinnler, 1996).

The most common alcohol, identified as a key odorant in most of the cheese types studied, is 1-octen-3-ol. Linoleic and linolenic acids are precursors of eight carbon aroma compounds such as this substance. In mould-ripened cheeses, in particular Camembert and Brie, the occurrence of this alcohol is related to

Penicillium metabolism (Karahadian, Josephson, & Lindsay, 1985a, b). This alcohol is a main odour-active compound of soft-cheeses, such as Camembert, natural and creamy Gorgonzola and water buffalo Mozzarella, but it is also a key odorant of a hard cheese such as Grana Padano (Table 1). 1-Octen-3-ol, with its characteristic green and mushroom-like notes and its low perception threshold, contributes significantly to the aroma profiles of these cheese varieties (Table 1). Moreover, the odour intensity of this alcohol can be enhanced by the presence of its corresponding ketone 1-octen-3-one (Kubíčková & Grosch, 1997). This suggestion is based on the findings of Meilgaard & Peppard (1986). They showed that the odour intensities of compounds having similar odour qualities are additive. Further, 1-octen 3-ol seems to impart a masking effect on the blue cheese odour of methyl ketones (Urbach, 1997).

The presence of branched-chain primary alcohols, such as 3-methyl-1-butanol, indicates the reduction of the aldehyde produced from leucine. It was identified as a minor odorant of bovine Mozzarella and confers a pleasant aroma of fresh cheese (Moio, Langlois, Etiévant, & Addeo, 1993).

Of the secondary alcohols, 2-heptanol has been identified as a key odorant of Gorgonzola, both natural and creamy, and Grana Padano cheeses. Secondary alcohols are formed by enzymatic reduction of the corresponding methyl ketones, which themselves are derived from fatty acids by β-oxidation or from β-ketoacids (Molimard & Spinnler, 1996).

Phenylethanol, identified in goat cheese and Gruyère (Table 1), is among the most odorous aromatic alcohols. Its very pleasant aroma presents rose flower notes. Phenylethanol production from phenylalanine seems to be essentially achieved by yeasts (Lee & Richard, 1984).

2.2. *Aldehydes*

Aldehydes originate from amino acids either by transamination, leading to an intermediate imide that can be decarboxylated, or by Strecker degradation. This reaction is simple and can occur without enzymatic catalysis during ripening (Keeney & Day, 1957). Aldehydes are transitory compounds in cheese because they are rapidly reduced to primary alcohols or even oxidised to the corresponding acids.

Branched-chain aldehydes probably originate from amino acid degradation via enzymatic processes (Moio, Dekimpe, Etiévant, & Addeo, 1993) as well as non-enzymatic reactions (Strecker degradation) (Griffith & Hammond, 1989). Within this group, 2-methylpropanal, 2-methylbutanal and 3-methylbutanal are formed from valine, isoleucine and leucine, respectively. 3-Methylbutanal was identified as a potent odorant in Camembert, aged Cheddar, together with 2-methylbutanal, Emmental and Gruyère cheese varieties. The branched aldehyde 3-methylpropanal was listed amongst the most potent odour compounds of Grana Padano cheese (Table 2). Griffith and Hammond (1989) reported malty aromas related to aldehydes produced from the branched aliphatic amino acids valine, isoleucine and leucine. 3-Methylbutanal presents a green malty odour (acrid pungent) but at low concentrations the odour becomes fruity and rather pleasant.

Straight-chain aldehydes, such as *n*-butanal, *n*-pentanal, *n*-hexanal and *n*-nonanal are quite common among the cheeses considered. They are characterised by green-grass and herbaceous aromas. Such compounds may also result from β-oxidation of unsaturated fatty acids (Collomb & Spahni, 1996) or even light-induced reactions, although such reactions are not likely to occur in cheese (Borle, Bosset, & Sieber, 2002). Straight-chain aldehydes are very unpleasant when their concentrations exceed certain thresholds. Within this group, the most commonly found odorant seems to be nonanal. It is important for the aroma of Grana Padano and water buffalo Mozzarella (Table 2). Further, the unsaturated form (*E*)-nonenal confers a pleasant green flavour to Pecorino and Ragusano (ripened for 4 and 8 months) cheese types (Carpino & Mallia, personal communication).

One of the important aromatic aldehydes is phenylacetaldehyde, formed by phenylalanine degradation. It is a major odour-active compound of Gruyère (Rychlik & Bosset, 2001a, b) and bovine Mozzarella (Moio et al., 1993).

2.3. *Ketones*

Ketones (Table 3) are common constituents of most dairy products. Due to their typical odours and their low perception thresholds, ketones, and especially methyl ketones, are primarily known for their contribution to the aroma of surface-mould ripened and blue-veined cheeses. In surface-ripened cheese, the synthesis of these compounds is related to the enzymatic activity of moulds (*P. roqueforti*, *P. camemberti* or *G. candidum*).

Fruity, floral and musty notes are associated with various methyl ketones such as 2-octanone, 2-nonanone, 2-decanone and 2-undecanone, while Blue cheese notes are attributed to 2-heptanone. 2-Heptanone is an important flavour compound of Emmental and natural and creamy Gorgonzola and 2-nonanone is another predominant methyl ketone in natural Gorgonzola and ripened Ragusano cheeses. Further, 2-undecanone seems to be a key aroma compound of Camembert (Table 3).

From a sensory point of view, another important odorant is 1-octen-3-one which has been commonly associated with mushroom odours. The production of this compound by *P. camemberti* probably derives from

Table 1
Alcohols identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($\mu g\,kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($\mu g\,kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
Primary alcohols	Ethanol	Dry, dust	Ched	OI 0.5, OI 1			Osme	P & T	1
	1-Propanol	Sweet (candy)	Ched	OI 1			Osme	P & T	1
	1-Pentanol	Fruity	Ched	OI 0.5			Osme	P & T	1
	1-Pentanol	Alcoholic, green	Gorg nat//creamy	15//ne	730 (water)	10	Charm/OAV	VD	13
	1-Pentanol	Balsamic	Grana Pad 12 M	12			Charm	VD	11
	Hexanol	Green	Mozz WB	*c* 92, % 3.2			Charm	VD	12
Primary branched alcohols	2-Methyl-1-propanol	Plastic, bad	Ched	OI 1			AEDA	P & T	1
	3-+2-Methyl-1-butanol	Alcoholic, green	Mozz Bov	*c* 200, % 6.9			Charm	VD	12
	3-+2-Methyl-1-butanol	Fusel oil, pomace	Gorg nat//creamy	210//600	300 (water)	15	Charm/OAV	VD	13
	2-Ethyl-l-hexanol		Mozz Bov	*c* 78, % 2.7			Charm	VD	12
	2-Ethyl-l-hexanol		Mozz WB	*c* 29, % 1			Charm	VD	12
Secondary alcohols	2-Propanol	Fruity	Ched	OI 0.5			Osme	P & T	1
	2-Pentanol	Fresh	Ragus 4 M	*c* 4, % 0.3			Charm	H-SPME	2
	2-Heptanol	Sweetish	Camemb	FD 32			AEDA	HVD	6
	2-Heptanol	"Queso curado" (ripened cheese)	FDG	*c* 64			Charm	MD	3
	2-Heptanol	Herbaceous, oily	**Gorg nat//creamy**	740//300	5 (water)	10	Charm/OAV	VD	13
	2-Heptanol	Green, earthy	**Grana Pad 12 M**	157			Charm	VD	11
	2-Heptanol	Fruity	Pecorino 6 M	*c* 5, % 0.4			Charm	H-SPME	2
	2-Nonanol	Fatty, green	Gorg nat//creamy	1200//100	75 (water)	10	Charm/OAV	VD	13
Unsaturated alcohols	3-Methyl-2-buten-1-ol	Cheese, fruity, green	Grana Pad 12 M	12			Charm	VD	11
	1-Octen-3-ol	Mushroom-like	**Camemb**	75, 130	n 34, rn 36 (SF oil)	7	AEDA/AECA/GCO-H/OAV	HVD	6, 7
	1-Octen-3-ol	Mushroom	Goat BC	ne			AEDA	VD	9

	1-Octen-3-ol	Mushroom, musty/ mouldy, earthy	**Gorg nat//creamy**	150//20	1 (water)	4, 5	Charm/OAV	VD	13
	1-Octen-3-ol	Mushroom-like, earthy	**Grana Pad 12 M**	13			Charm	VD	11
	1-Octen-3-ol	Mushroom-like, undergrowth, musk	Mozz Bov	*c* 60, % 2			Charm	VD	12
	1-Octen-3-ol	Mushroom-like, undergrowth, musk	**Mozz WB**	*c* 635, % 22.5			Charm	VD	12
	(*Z*)-1,5-Octadien-3-ol	Earthy	Camemb	FD 16			AEDA	HVD	6
Aromatic alcohols	Phenylethanol	Rose flower	Mozz Bov	ne			Charm	VD	12
	Phenylethanol	Rose flower	Mozz WB	*c* 22, % 0.7			Charm	VD	12
	Phenylethanol	Rose	Goat BC	+ +			AEDA/Osme	VD	9
	2-Phenylethanol	Floral	Camemb	130, 137	n 211, rn 122 (SF oil)	7	AEDA/OAV	HVD	6, 7
	2-Phenylethanol	Rosy	Ched BF	FD 243			AEDA	HVT	16
	2-Phenylethanol	Honey-like	Gru	ne			AEDA	HVD	14
	2-Phenylethanol	Roses	Roncal	*c* 4, % 0.4			Charm	SFE	8

[a] Within each group, compounds are listed according to increasing molecular weight; compounds in bold were identified as main odorants in the corresponding cheese types.

[b] Odour description assigned during GC-O analysis. No descriptors are specified if the information was missing in the corresponding bibliographic reference.

[c] Camemb: Camembert; Ched: Cheddar; Ched BF: British Farmhouse Cheddar; FDG: Flor de Guia cheese; Goat BC: "Bouton de Culotte" goat cheese; Gorg nat//creamy: Gorgonzola natural//creamy; Grana Pad 12 M: Grana Padano ripened for 12 months; Gru: Gruyère; Mozz WB: water buffalo Mozzarella; Mozz Bov: bovine Mozzarella; Pecorino 6 M: Pecorino ripened for 6 months; Ragus 4 M: Ragusano ripened for 4 months; Roncal: Roncal cheese (ewe's cheese). The cheese types in bold are those in which the corresponding odorant was found to be a major one.

[d] If not otherwise specified, numbers correspond to concentrations in $\mu g\,kg^{-1}$; c (charm value) $= d^{(n-1)}$ (d, dilution value; n, last dilution perceived); %: percentage area of the odour-active regions of the charm chromatogram; OI: odour intensity (direct intensity measurement) range 1–5; +: odour potency (one assessor, range + to + + +); FD: dilution factor; ne: not evaluated.

[e] n: nasal; rn: retronasal; SF oil: sunflower oil.

[f] Threshold references.

[g] AECA: aroma extract concentration analysis; AEDA: aroma extract dilution analysis; Charm: combined hedonic aroma response measurement; GCO-H: static headspace gas chromatography-olfactometry; OAV: odour activity value (concentration to odour threshold ratio).

[h] H-SPME: headspace solid phase microextraction; (H)VD: (high) vacuum distillation; HVT: high vacuum transfer; MD: molecular distillation; P & T: purge and trap; SFE: supercritical fluid extraction.

[i] Bibliographic references.

Reference numbers are as follows: (1) Arora, Cormier, and Lee (1995); (2) Carpino and Mallia (personal communication); (3) Gonzalez-Mendoza and Diaz-Rodriguez (1993); (4) Karahadian, Josephson, and Lindsay (1985a); (5) Karahadian, Josephson, and Lindsay (1985b); (6) Kubíckova and Grosch (1997); (7) Kubícková and Grosch (1998b); (8) Larráyoz et al. (2002, personal communication, paper submitted); (9) Le Quéré, Septier, and Demaizières (1996); (10) Maarse and Visscher (1989); (11) Moio and Addeo (1998); (12) Moio, Langlois, Etiévant, and Addeo (1993); (13) Moio, Piombino, and Addeo (2000); (14) Rychlik and Bosset (2001a); (15) Siek, Albin, Sather, and Lindsay (1969); (16) Suriyaphan, Drake, Chen, and Cadwallader (2001).

Table 2
Aldehydes identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($\mu g\,kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($\mu g\,kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
Straight-chain aldehydes	Acetaldehyde	Green	Camemb	15, 25	n 0.22, rn 7.1 (SF oil)	7	GCO-H/OAV	HVD	6, 7
	Acetaldehyde	Sweet, pungent	Ched RF//LF	vol 20//vol 10			GCO-H	HVD	19
	Acetaldehyde	Green	Gru	vol 10			GCO-H	HVD	14
	Pentanal	Chemical	Ched	OI 1			Osme	P & T	1
	Hexanal	Green	Camemb	124, 144	n 120, rn 73 (SF oil)	7	AEDA/GCO-H/OAV	HVD	6, 7
	Hexanal	Slightly fruity (balsam)	Ched	OI 3			Osme	P & T	1
	Hexanal	Green	Ched RF//LF	vol 40//vol 40			GCO-H	HVD	19
	Heptanal	Soapy	Ched	OI 3			Osme	P & T	1
	Heptanal	Herbaceous	Mozz WB	*c* 78, % 2.7			Charm	VD	12
	Octanal	Fatty, green	Mozz WB	*c* 14, % 0.5			Charm	VD	12
	Nonanal	Green, fatty	Ched RF//LF	FD 16//FD 8			AEDA	HVD	19
	Nonanal	"Nata" (cream)	FDG	*c* 56			Charm	MD	3
	Nonanal	Green, grass-like, tallowy	**Grana Pad 12 M**	tr			Charm	VD	11
	Nonanal	Green, tallowy, animals	Mozz Bov	*c* 110, % 3.8			Charm	VD	12
	Nonanal	Green, tallowy, animals	**Mozz WB**	*c* 358, % 13			Charm	VD	12
	Nonanal	Soapy	Pecorino 6 M	*c* 20, % 1.5			Charm	H-SPME	2
	Nonanal	Soapy	Ragus 4 M//8 M//12 M	*c* 37, % 2.7//*c* 135% 4.6//*c* 30, % 1.2			Charm	H-SPME	2
	Decanal	Green	Mozz WB	*c* 55, % 1.9			Charm	VD	1
	n-Decanal	Green/nutty	Pecorino 6 M	*c* 27, % 2			Charm	H-SPME	2
	n-Decanal	Nutty	Ragus 8 M, 12 M	*c* 202, % 6.9//*c* 135, % 4.6			Charm	H-SPME	2
Branched aldehydes	2-Methylpropanal	Green, malty	Camemb	vol 20			GCO-H	HVD	6
	2-Methylpropanal	Floral	Ched	OI 1			Osme	P & T	1
	2-Methylpropanal	Malty	Gru	vol 20			GCO-H	HVD	14
	2-Methylbutanal	Green, malty	Camemb	FD 4, vol 10			AEDA/GCO-H	HVD	6
	2-Methylbutanal	Slightly caramel, nutty	Ched	OI 0.5			Osme	P & T	1
	2-Methylbutanal	Malty	Gru	255	n 10 (SF oil)	24	AEDA/GCO-H/OAV	HVD	14, 23
	3-Methylbutanal	Green, malty	**Camemb**	94, 142	n 13, rn 10.8 (SF oil)	7	AEDA/AECA/GCO-H/OAV	HVD	6, 7
	3-Methylbutanal		**Emm**	64, 87	n 5.4, rn 10.8 (SF oil)	21	AEDA	HVD	21, 22
	3-Methylbutanal	Herbaceous	Gorg nat//creamy	260//220	12 (water)	18	Charm/OAV	VD	13
	3-Methylbutanal	Malty	**Gru**	219	n 13 (SF oil)	21	AEDA/GCO-H/OAV	HVD	14, 13
	2- + 3-Methylbutanal	Tootsie Rolls	**Ched Ag**	OP 81			AEDA	MD	17

Unsaturated aldehydes	(*Z*)-4-Heptenal	Biscuit-like	Gru	FD 32			AEDA	HVD	14
	(*E*)-2-Nonenal	Cardboard-like	Ched RF//LF	FD 8//FD 32			AEDA	HVD	19
	(*E*)-2-Nonenal	Missing	Emm	FD<4, FD 64			AEDA	HVD	22
	(*E*)-2-Nonenal	Green	Gru	FD 128			AEDA	HVD	14
	(*E*)-2-Nonenal	Green	Pecorino 6 M	*c* 101, % 7.5			Charm	H-SPME	2
	(*E*)-2-Nonenal	Green	**Ragus 4 M, 8 M, 12 M**	*c* 352, % 26.1//*c* 274, % 9.4// *c* 41, % 1.7			Charm	H-SPME	2
	(*Z*)-2-Nonenal	Fatty, tallowy	Ched RF//LF	FD 16//FD 8			AEDA	HVD	19
	(*Z*)-2-Nonenal	Missing	Emm	FD < 4, FD 64			AEDA	HVD	22
	(*Z*)-2-Nonenal	Green	**Gru**	FD 32			AEDA	HVD	14
	(*Z*)-2-Nonenal	Hay	Pecorino 6 M	*c* 71, % 5.3			Charm	H-SPME	2
	(*Z*)-2-Nonenal	Hay	Ragus 4 M, 8 M, 12 M	*c* 48, % 3.6//*c* 192, % 6.6// *c* 146, % 6			Charm	H-SPME	2
	trans-4,5-Epoxy-2-(*E*)-decenal	Metallic	Ched RF//LF	FD 16//FD 16			AEDA	HVD	19
	(*E,E*)-2,4-Nonadienal	Deep-fried	Gru	FD 32			AEDA	HVD	14
	(*E,Z*)-2,6-Nonadienal	Melon-like, cucumber	Ched BF	FD 9			AEDA	HVT	16
	(*E,E*)-2,4-Decadienal	Deep-fried	Gru	FD 32			AEDA	HVD	14
	trans-trans-2,4-Decadienal	Fried	Ragus 12 M	*c* 31, % 1.3			Charm	H-SPME	2
	2,4-Dodecadienal	"Lácteo" (lactic)	FDG	*c* 171			Charm	MD	3
Aromatic aldehydes	Phenylacetaldehyde	Honey-like	Camemb	FD 64			AEDA/AECA	HVD	6
	Phenylacetaldehyde	Rosy, styrene	Ched BF	FD 27			AEDA	HVT	16
	Phenylacetaldehyde	Flower, (broom: *Spartium junceum*)	Gorg nat// creamy	20//8	1 (water)	10	Charm/OAV	VD	13
	Phenylacetaldehyde	Honey-like	**Gru**	20	n 25 (SF oil)	20	AEDA/OAV	HVD	14
	Phenylacetaldehyde	Flower, (broom: *Spartium junceum*)	Mozz Bov	*c* 199, % 7			Charm	VD	12
	Phenylacetaldehyde	Flower, (broom: *Spartium junceum*)	Mozz WB	*c* 39, % 1.4			Charm	VD	12
	Phenylacetaldehyde	Daisy	Ragus 8 M	*c* 39, % 1.3			Charm	H-SPME	2

[a] Refer to footnote a in Table 1.
[b] Refer to footnote b in Table 1.
[c] Ched Ag: aged Cheddar; Ched RF//LF: regular fat//low fat mild Cheddar; Emm: Emmental; Ragus 4 M, 8 M, 12 M: Ragusano ripened for 4, 8, 12 months. For other abbreviations see footnote c in Table 1.
[d] tr: traces; vol: smallest headspace volume sufficient to perceive the corresponding odorant at the GC-O sniffing port. For other abbreviations see footnote d in Table 1.
[e] Refer to footnote e in Table 1.
[f,i] Reference numbers are as follows (for references 1–16 refer to footnotes f and i in Table 1): (17) Christensen and Reineccius (1995); (18) Margalith (1981); (19) Milo and Reineccius (1997); (20) Pfnür (1988); (21) Preininger and Grosch (1994); (22) Preininger, Rychlik, and Grosch (1994); (23) Rychlik and Bosset (2001b); (24) Wagner and Grosch (1998).
[g] Refer to footnote g in Table 1.
[h] Refer to footnote h in Table 1.

Table 3
Ketones identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($\mu g\,kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($\mu g\,kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
	2-Propanone (acetone)	Wood pulp, hay	Ched	OI 2.5			Osme	P & T	1
	2-Butanone	Butterscotch	**Ched**	OI 4			Osme	P & T	1
	2-Pentanone	Orange peel	Ched	OI 1			Osme	P & T	1
	2-Pentanone	Sweet, fruity	Grana Pad 12 M	296			Charm	VD	11
	2-Heptanone		**Emm**	363, 380	n 1500, rn 1500 (SF oil)	21	AEDA/OAV	HVD	21, 22
	2-Heptanone	Gorgonzola cheese	**Gorg nat//creamy**	500//400	9 (water)	26	Charm/OAV	VD	13
	2-Heptanone	Fruity, fatty, spicy, herbaceous	Grana Pad 12 M	536			Charm	VD	11
	2-Heptanone	Green	Gru	FD 64			AEDA	HVD	14
	2-Heptanone	Animals, blue cheese	Mozz WB	*c* 75, % 2.6			Charm	VD	12
	2-Octanone	Fruity	Mozz WB	*c* 97, % 3.4			Charm	VD	12
	3-Octanone	Earthy	Camemb	FD 32			AEDA	HVD	6
	2-Nonanone	Malty, fruity	Camemb	FD 16			AEDA	HVD	6
	2-Nonanone	Gorgonzola cheese	**Gorg nat**//creamy	3000//810	20 (water)	10	Charm/OAV	VD	13
	2-Nonanone	Hot milk, smoked cheese	Mozz WB	*c* 29, % 1			Charm	VD	12
	2-Nonanone	Hot milk	**Ragus** 8 M//**12 M**	*c* 146, % 5//*c* 237, % 9.7			Charm	H-SPME	2
	2-Undecanone	Musty	Gorg nat//creamy	300//24	7 (water)	26	Charm/OAV	VD	13
	2-Undecanone	Floral	**Camemb**	180, 700	n 3400, rn 2400	7	AEDA/AECA/GCO-H/OAV	HVD	6, 7
	2-Undecanone	"Afrutado" (fruity)	FDG	*c* 20			Charm	MD	3
	2-Tridecanone	"Cáprico" (goaty)	FDG	*c* 181			Charm	MD	3
	2-Pentadecanone	"Humedad" (moisture)	FDG	*c* 20			Charm	MD	3
Unsaturated ketones	**1-Octen-3-one**	Mushroom-like	**Camemb**	2.1, 2.2	n 10, rn 0.3 (SF oil)	25	AEDA/AECA/GCO-H/OAV	HVD	6
	1-Octen-3-one	Mushroom	Ched BF	FD 9			AEDA	HVT	16
	1-Octen-3-one	Mushroom, smoky,	**Ched Ag**	OP 9			AEDA	MD	17

		metallic							
	1-Octen-3-one	Mushroom	Ched RF//LF	FD 4//FD 8, vol 20//vol 20			AEDA/GCO-H	HVD	19
	1-Octen-3-one		**Emm**	0.23, 0.5	n 10, rn 0.3 (SF oil)	25	AEDA/OAV	HVD	21, 22
	1-Octen-3-one	Mushroom	Pecorino 6 M	*c* 41, % 3.1			Charm	H-SPME	2
	1-Octen-3-one	Mushroom	**Ragus 4 M**//8 M//12 M	*c* 253, % 18.8//*c* 163, % 5.6// *c* 168, % 6.9			Charm	H-SPME	2
	8-Nonen-2-one	Blue cheese	Gorg nat//creamy	240//150			Charm/OAV	VD	13
	β-Damascenone	Apple-like	Camemb	FD 32			AEDA	HVD	6
	β-Damascenone	Apple sauce	Ched BF	FD 81			AEDA	HVT	16
	(*E*)-*β*-Damascenone	Fruity, peach-like	Ched RF//LF	FD 32//FD 64			AEDA	HVD	19
	2,3-Butanedione (diacetyl)	Buttery	**Camemb**	74, 110	n 10, rn 10 (SF oil)	7	AEDA/AECA/GCO-H/OAV	HVD	6, 7
	2,3-Butanedione	Cheesy, caramel	**Ched**	OI 5			Osme	P & T	1
	2,3-Butanedione	Butter, mild cheddar	Ched Ag	OP 3			AEDA	MD	17
	2,3-Butanedione	Butter-like	**Ched RF//LF**	210//251			AEDA/GCO-H/OAV	HVD	19
	2,3-Butanedione		**Emm**	98	n 10, rn 10 (SF oil)	21	AEDA/OAV	HVD	21, 22
Further ketones	**3-Hydroxy-2-butanone** (acetoin)	Sour milk	**Ched**	OI 4			Osme	P & T	1
	3-Hydroxy-2-pentanone	Herbaceous, truffle	Mozz WB	*c* 138, % 4.9			Charm	VD	12
	2-Hydroxy-3-pentanone	Truffle, earth-nut	Mozz WB	*c* 94, % 3.3			Charm	VD	12
	3-Methyl-2-pentanone	"Bombón" (candy)	FDG	*c* 162			Charm	MD	3

[a] Refer to footnote a in Tables 1 and 2.
[b] Refer to footnote b in Tables 1 and 2.
[c] Refer to footnote c in Tables 1 and 2.
[d] Refer to footnote d in Tables 1 and 2.
[e] Refer to footnote e in Tables 1 and 2.
[f,i] Reference numbers are as follows (for references 1–24 refer to footnotes f and i in Tables 1 and 2): (25) Guth and Grosch (1990); (26) Stahl (1973).
[g] Refer to footnote g in Tables 1 and 2.
[h] Refer to footnote h in Tables 1 and 2.

Table 4
Esters identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($\mu g\,kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($\mu g\,kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
Straight-chain esters	Ethyl acetate	Fruity, pinapple	Ched	OI 1			Osme	P & T	1
	Ethyl acetate	Juicy fruit gum, apples	Ched Ag	OP 3			AEDA	MD	17
	Ethyl butyrate (ethyl butanoate)	Pleasant, green fruit	**Ched**	OI 4			Osme	P & T	1
	Ethyl butyrate	Sweet, fruity, apple blossom	**Ched Ag**	OP 243			AEDA	MD	17
	Ethyl butyrate	Bubble gum, fruity	Ched BF	FD 27			AEDA	HVT	16
	Ethyl butyrate		**Emm**	26, 50	n 28, rn 3.5 (SF oil)	21	AEDA/OAV	HVD	21, 22
	Ethyl butyrate	"Medicina" (medicine)	FDG	*c* 190			Charm	MD	3
	Ethyl butyrate	Fruity	Goat BC	ne			AEDA	VD	9
	Ethyl butyrate	Fruity, green	Gorg nat//**creamy**	ne//15	1 (water)	4, 5, 27	Chram/OAV	VD	13
	Ethyl butyrate	Fruity, green	**Grana Pad 12 M**	362			Charm	VD	11
	Ethyl butyrate	Fruit	Mozz Bov	*c* 112, % 3.8			Charm	VD	12
	Ethyl butyrate	Fruity, sweet	**Pecorino 6 M**	*c* 217, %16.2			Charm	H-SPME	2
	Ethyl butyrate	Fruity, sweet	Ragus 4 M//8 M//12 M	*c* 40, % 3//*c* 205, % 7// *c* 146, % 6			Charm	H-SPME	2
	Pentyl acetate	Fruity	Gorg nat//creamy	10//ne	1 (water)	10	Charm/OAV	VD	13
	Propyl butyrate	Fruity	Ragus 4 M//12 M	*c* 29, % 2.2//*c* 6, % 0.2			Charm	H-SPME	2
	Ethyl hexanoate (ethyl caproate)	Fruity, malty	Camemb	FD 32 , vol 20			AEDA/GCO-H	HVD	6
	Ethyl hexanoate	Young cheese	Ched	OI 1			Osme	P & T	1
	Ethyl hexanoate	Fruity	Ched BF	FD 27			AEDA	HVT	16
	Ethyl hexanoate	Fruit, melon, sour fruit	**Ched Ag**	OP 81			AEDA	MD	17
	Ethyl hexanoate		**Emm**	62, 142	n 40, rn 20 (SF oil)	21	AEDA/OAV	HVD	21, 22
	Ethyl hexanoate	"Jarabe" (syrup)	FDG	*c* 190			Charm	MD	3
	Ethyl hexanoate	Mouldy	Goat BC	ne			AEDA	VD	9
	Ethyl hexanoate	Fruity, apple	**Gorg nat**//creamy	80//30	1 (water)	15	Charm/OAV	VD	13
	Ethyl hexanoate	Fruity, unripe fruit, apple	**Grana Pad 12 M**	993			Charm	VD	11
	Ethyl hexanoate	Fruit, green	Mozz WB	*c* 191, % 6.6			Charm	VD	12
	Ethyl hexanoate	Orange	**Pecorino 6 M**	*c* 136, % 10.2			Charm	H-SPME	2

	Ethyl hexanoate	Orange	**Ragus 4 M//8 M//12 M**	*c* 377, % 28// *c* 264, % 9.1// *c* 237, % 9.7			Charm	H-SPME	2
	Ethyl octanoate	Fruity	Ched BF	FD 81			AEDA	HVT	16
	Ethyl octanoate		Emm	FD <4, FD 32			AEDA	HVD	22
	Ethyl octanoate	"Caramel" (caramel)	**FDG**	*c* 1462			Charm	MD	3
	Ethyl octanoate	Fruity, apple-like	Gorg nat//creamy	130//100			Charm	VD	13
	Ethyl octanoate	Green, fruity	Grana Pad 12 M	214			Charm	VD	12
	Ethyl octanoate	Fatty, fruity	Gru	FD 32			AEDA	HVD	14
	Ethyl octanoate	Orange	Pecorino 6 M	*c* 14, % 1			Charm	H-SPME	2
	Ethyl dodecanoate	"Queso de flor" ("Flor" cheese)	FDG	*c* 3			Charm	MD	3
Branched esters	Methyl-2-methylbutanoate	Sweet	Gru	FD 16, vol 20			AEDA/GCO-H	HVD	14
	Ethyl isobutanoate	Unripe fruit, green	**Mozz Bov**	*c* 580, % 20			Charm	VD	12
	3-Methylbutyl acetate	Fruity, banana	Gorg nat//creamy	6//15	3 (water)	28	Charm/OAV	VD	13
	3-Methylbutyl acetate	Fruity, banana, candy circus peanuts	Grana Pad 12 M	5			Charm	VD	11
	Ethyl-2-methylbutanoate	Sweet	Gru	FD 64, vol 2.5			AEDA/GCO-H	HVD	14
	Ethyl-3-methylbutanoate		**Emm**	<0.1, 0.9	n 0.1, rn 0.1 (SF oil)	21	AEDA/OAV	HVD	21, 22
	Ethyl-3-methylbutanoate	Fresh cheese, cheese factory	**Mozz Bov**	*c* 900, % 31			Charm	VD	12
	Isobutyl butanoate	Fruity	Gorg nat//creamy	6//5			Charm	VD	13
	Methyl octanoate		Emm	FD <4, FD 16			AEDA	HVD	22
	3-Octyl acetate	Floral	Gorg nat//creamy	10//ne			Charm	VD	13
	2-Methylbutyl hexanoate	Minty	Grana Pad 12 M	2			Charm	VD	11
Aromatic esters	Ethyl benzoate	Floral	Gorg nat//creamy	1.5//tr	60 (water)	10	CharmOAV	VD	13
	Phenethyl acetate (phenylethyl acetate)	Floral, rose-like	**Camemb**	250, 320	n 137, rn 212 (SF oil)	7	AEDA/AECA/OAV	HVD	6, 7

[a] Refer to footnote a in Tables 1 and 2.
[b] Refer to footnote b in Tables 1 and 2.
[c] Refer to footnote c in Tables 1 and 2.
[d] Refer to footnote d in Tables 1 and 2.
[e] Refer to footnote e in Tables 1 and 2.
[f,i] Reference numbers are as follows (for references 1–26 refer to footnotes f and i in Tables 1–3): (27) Ahmed, Dennison, Dougherty, and Shaw (1978); (28) Moinas, Groux, and Horman (1975).
[g] Refer to footnote g in Tables 1 and 2.
[h] Refer to footnote h in Tables 1 and 2.

the linoleic and linolenic pathways (Karahadian, Josephson, & Lindsay, 1985a, b). 1-Octen-3-one is a potent odorant of Camembert, aged Cheddar, Emmental and Ragusano ripened for 4 months (Table 3).

One of the most important diketones is 2,3-butanedione (diacetyl). This component is obtained from pyruvate stemming from lactose and citrate metabolism. The production of 2,3-butanedione is mainly due to the activity of lactic acid bacteria, especially *Lactococcus lactis* ssp. *lactis* biovar *diacetylactis* and *Leuconostoc* spp. (Welsh, Murray, & Williams, 1989). This volatile compound is appreciated for its buttery and nut-like notes and was identified as a key aroma component of Camembert, Cheddar and Emmental (Table 3).

2.4. Esters

Esters (Table 4) are common cheese volatiles. Esterification reactions occur between short- to medium-chain fatty acids and primary and secondary alcohols derived from lactose fermentation or from amino acid catabolism (Bosset & Liardon, 1984).

Most esters encountered in cheese are described as having sweet, fruity and floral notes. Especially ethyl esters are known for their important role in the formation of a fruity character in cheese. Some of these esters have a very low perception threshold. Further, these compounds can contribute to the aroma of cheese by minimising the sharpness and the bitterness imparted by fatty acids and amines, respectively (Gallois & Langlois, 1990). Ethyl butanoate has been identified as one of the most potent odorants of Cheddar, Emmental, creamy Gorgonzola, Grana Padano and Pecorino, whereas ethyl hexanoate plays an important role in the aroma profiles of aged Cheddar, natural Gorgonzola, Grana Padano, Pecorino and Ragusano cheeses (Table 4). A further ester, ethyl octanoate, seems to be significant in the formation of the aroma of Flor de Guia cheese (Gonzalez-Mendoza & Diaz-Rodriguez, 1993).

The sensory characteristics of bovine Mozzarella cheese seem to depend primarily on the branched esters ethyl isobutanoate (ethyl-2-methylpropanoate) and ethyl-3-methylbutanoate (Moio et al., 1993). The latter compound also plays an important role in the aroma of Emmental cheese (Preininger & Grosch, 1994).

Phenethyl acetate is one of the most important aromatic esters. This compound imparts a floral odour note to Camembert cheese (Kubícková & Grosch, 1997).

2.5. Lactones

Lactones (Table 5) are cyclic esters in which the acid and the alcohol functions belong to the same molecule. In cheese, it is suggested that they are generated by hydrolysis of hydroxy-fatty acid triglycerides (normal constituents of milk fat), followed by lactonisation (Jolly & Kosikowski, 1975). Further mechanisms have also been proposed (Adda, Gripon, & Vassal, 1982) but none of them has ever been proved.

The presence of different γ- and δ-lactones in soft-cheese, such as Camembert, might be of importance in the final aroma due to their fruity notes and their low perception thresholds. Lactones, in fact, are generally associated with pronounced peach, apricot and coconut odour qualities. One of the most common and important lactones identified in cheese is δ-decalactone. This compound is a key odorant of Camembert and Emmental cheese varieties. However, the sensory characteristics of goat cheese and British farmhouse Cheddar seem to depend on two other lactones: δ-octalactone and δ-dodecalactone, respectively (Table 5).

2.6. Furans

Chiral 3(2H)- and 2(5H)-furanones (Table 6) are known to be powerful flavour compounds. They are aroma constituents of many fruits and processed foods. Due to their pleasant taste and odour, they are produced synthetically on an industrial scale and they are widely used as flavouring agents for food and beverages (Bruche, Dietrich, & Mosandl, 1995; Blank & Fay, 1996). However, little is known about the influence of furans on cheese flavour. There is evidence that these compounds may contribute to the sensory properties of some cheese varieties. Table 6 shows that 4-hydroxy-2,5-dimethyl-3(2 H)-furanone (furaneol) is a key odorant of Emmental cheese. In processed food, furaneol is probably formed in the course of cooking. Model experiments have revealed that this compound is produced by thermal degradation of fructose or 6-deoxyhexoses, in the presence of amines and amino acids via Maillard reaction (see Pischetsrieder & Severin, 1994 as cited by Hecquet, Sancelme, Bolte, & Demuynck, 1996). Furaneol has been detected in whey permeate supplemented with amino acids and inoculated with *Lactobacillus helveticus* (Kowalewska et al., 1985). For this reason, Preininger and coworkers (1994) suggest that this component may be produced in a similar way in Emmental cheese, as *L. helveticus* belongs to the micro-organisms involved in the ripening of this cheese.

Another important furan is 5-ethyl-4-hydroxy-2-methyl-3(2H)-furanone (homofuraneol). This compound contributes strongly to the flavour of regular and low fat Cheddar (Milo & Reineccius, 1997) and Emmental (Preininger & Grosch, 1994; Preininger, Rychlik, & Grosch, 1994) cheese types. This volatile has been detected also in soy sauce (Nunomura, Sasaki, Asao, & Yokotsuka, 1976) where it is an important odorant on the basis of its low odour threshold value and its caramel-like, sweet odour qualities.

Table 5
Lactones identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($\mu g\,kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($\mu g\,kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
	δ-Octalactone	Coconut-like	Camemb	FD 32			AEDA	HVD	6
	δ-Octalactone	Fruity	**Goat BC**	+ +			AEDA/Osme	VD	9
	δ-Octalactone	Peach-like	Mozz Bov	*c* 49, % 1.7			Charm	VD	12
	δ-Octalactone	Peach-like	Mozz WB	*c* 58, % 2			Charm	VD	12
	δ-Decalactone	Coconut-like	**Camemb**	910, 1080	n 400, rn 1600 (SF oil)	7	AEDA/AECA/OAV	HVD	6, 7
	δ-Decalactone	Peachy, coconut	Ched BF	FD 27			AEDA	HVT	16
	δ-Decalactone	Coconut-like	Ched RF//LF	2350//1060			AEDA/OAV	HVD	19
	δ-Decalactone		**Emm**	937, 1332	n 400, rn 1600 (SF oil)	21	AEDA/OAV	HVD	21, 22
	δ-Decalactone	Creamy, coconut, peach	Grana Pad 12 M	4			Charm	VD	11
	δ-Decalactone	Sweet, coconut-like	Gru	FD 64			AEDA	HVD	14
	γ-Decalactone	Coconut	Ched BF	FD 27			AEDA	HVT	16
	δ-Dodecalactone	Cheesy, coconut	**Ched BF**	FD 729			AEDA	HVT	16
	δ-Dodecalactone	Sweet, soapy	Ched RF//LF	FD 8//FD 16			AEDA	HVD	19
	δ-Dodecalactone		Emm	FD <4, FD 16			AEDA	HVD	22
	δ-Dodecalactone	Coconut powder, buttery, peach	Grana Pad 12 M	tr			Charm	VD	11
	γ-Dodecalactone	Peach, almonds, herbs, lilacs, fruit, toffee	Roncal	*c* 8, % 2.1			Charm	SFE	8
Unsaturated lactones	(*Z*)-6-Dodecen-γ-lactone	Green-fruity	Camemb	FD 16			AEDA/AECA	HVD	6
	(*Z*)-6-Dodecen-γ-lactone	Soapy	Ched RF//LF	268//263			AEDA/OAV	HVD	19
	(*Z*)-6-Dodecen-γ-lactone		Emm	FD 16, FD 512			AEDA	HVD	22
	(*Z*)-6-Dodecen-γ-lactone	Sweet	Gru	FD 32			AEDA	HVD	14
	Cis-Dodec-6-eno-γ-lactone	Lemon, toffee, peach, liqueur	Roncal	*c* 8, % 6.4			Charm	SFE	8

[a] Refer to footnote a in Tables 1 and 2.
[b] Refer to footnote b in Tables 1 and 2.
[c] Refer to footnote c in Tables 1 and 2.
[d] Refer to footnote d in Tables 1 and 2.
[e] Refer to footnote e in Tables 1 and 2.
[f,i] For references 1–22 refer to footnotes f and i in Tables 1 and 2.
[g] Refer to footnote g in Tables 1 and 2.
[h] Refer to footnote h in Tables 1 and 2.

Table 6
Furans identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($\mu g\,kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($\mu g\,kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
Furans	3-Hydroxy-4,5-dimethyl-2(5 H)-furanone (sotolon)		Camemb	FD 64			AEDA	HVD	6
	3-Hydroxy-4,5-dimethyl-2(5 H)-furanone	Curry, seasoning	Ched BF	FD 81			AEDA	HVT	16
	3-Hydroxy-4,5-dimethyl-2(5 H)-furanone	Seasoning-like	Gru	FD 16			AEDA	HVD	14
	4-Hydroxy-2,5-dimethyl-3(2 H)-furanone (furaneol)		Camemb	FD 32			AEDA	HVD	6
	4-Hydroxy-2,5-dimethyl-3(2 H)-furanone	Sweet, burnt, sugar	Ched BF	FD 9			AEDA	HVT	16
	4-Hydroxy-2,5-dimethyl-3(2 H)-furanone	Caramel	Ched RF//LF	52//160			AEDA/OAV	HVD	19
	4-Hydroxy-2,5-dimethyl-3(2 H)-furanone		**Emm**	824, 2035	n 25, rn 4 (SF oil)	21	AEDA/OAV		21, 22
	4-Hydroxy-2,5-dimethyl-3(2 H)-furanone	Strawberry-like	Gru	FD 32			AEDA	HVD	14
	4-Hydroxy-2-ethyl-5-methyl-3(2H)-furanone		Camemb	FD 2			AEDA	HVD	6
	4-Hydroxy-2-ethyl-5-methyl-3(2H)-furanone	Strawberry-like	Gru	FD 32			AEDA	HVD	14
	5-Ethyl-4-hydroxy-2-methyl-3(2H)-furanone (homofuraneol)	Caramel	**Ched RF//LF**	52//160			AEDA/OAV	HVD	19
	5-Ethyl-4-hydroxy-2-methyl-3(2H)-furanone		**Emm**	141, 222	n 6, rn 1.5 (SF oil)	21	AEDA/OAV	HVD	21, 22
	5-Heptylhydro-2(3H)-furanone	"Queso viejo" (old cheese)	**FDG**	*c* 16364			Charm	MD	3

[a] Refer to footnote a in Tables 1 and 2.
[b] Refer to footnote b in Tables 1 and 2.
[c] Refer to footnote c in Tables 1 and 2.
[d] Refer to footnote d in Tables 1 and 2.
[e] Refer to footnote e in Tables 1 and 2.
[f,i] For references 1–22 refer to footnotes f and i in Tables 1 and 2.
[g] Refer to footnote g in Tables 1 and 2.
[h] Refer to footnote h in Tables 1 and 2.

Intermediates of the pentose-phosphate cycle are important precursors in the biosynthesis of homofuraneol. However, the formation of this compound during processing is not yet well understood (Blank & Fay, 1996). Sensory analysis of Emmental cheese indicated that this component, together with furaneol, contributes strongly to the mild sweet and nut-like aroma of this cheese. The aroma of Flor the Guia cheese seems to depend primarily on another furan with a note of old cheese: 5-heptylhydro-2(3 H)-furanone (Table 6).

3. Alkaline components

3.1. Nitrogen-containing compounds

Among nitrogen-containing compounds (Table 7), indole is a main odorant of water buffalo Mozzarella and has a characteristic musty odour, reminiscent of stables (Moio et al., 1993). This volatile is likely to be a degradation product of tryptophan. Yeasts, micrococci and *Brevibacterium linens* are capable of cleaving the side chain of tryptophan releasing indole (Parliment, Kolor, & Rizzo, 1982; Jollivet, Bézenger, Vayssier, & Belin, 1992).

Skatole is another important nitrogen-containing compound which seems to contribute significantly to the aroma profile of Emmental cheese (Preininger & Grosch, 1994; Preininger et al., 1994).

3.2. Pyrazines

Pyrazines (Table 7) have been claimed as important contributors to cheese flavour, especially in the case of Cheddar and Gruyère. For example, the perception threshold of 3-isopropyl-2-methoxypyrazine is very low and this may explain its importance in the formation of an earthy soil character in British farmhouse Cheddar (Suriyaphan, Drake, Chen, & Cadwallader, 2001). This compound originates from L-valine degradation as found in *Pseudomonas taetrolens* (Gallois, 1984). However, in Camembert cheese, this pyrazine is responsible for a rotten soil and raw potato-like aroma defect (see Masuda & Mihara, 1988 as quoted by Molimard & Spinnler, 1996). In British farmhouse Cheddar another pyrazine, 2-isobutyl-3-methoxypyrazine, seems to be responsible for its bell-pepper-like note. The sensory evaluation of Gruyère cheese aroma revealed that 2-ethyl-3,5-dimethylpyrazine and 2,3-diethyl-5-methylpyrazine are also key odorants of this type of cheese (Rychlik & Bosset, 2001a, b).

3.3. Sulphur compounds

Volatile S-compounds (Table 7) play an important role in the flavour of cheese as reviewed by Molimard and Spinnler (1996) and McSweeney and Sousa (2000). Sulphur compounds essentially originate from methionine degradation and result from cleavage of a bond between carbon and sulphur by a methionine-demethiolase (Yvon & Rijnen, 2001). These components are described as having strong garlic and very ripe cheese odours (Table 7). Moreover, their perception thresholds are very low and so they are probably involved in the final aroma of mould-surface ripened and soft smear cheeses (Berger, 1999).

The most common S-compound in cheese is methional (3-methylthiopropanal). This volatile, which can be produced by Strecker degradation, has a characteristic boiled potato and acrid pungent odour and plays an important role in the aroma profiles of a varieties of cheeses such as Camembert, Cheddar (British farmhouse, regular and low fat), Emmental, goat cheese, creamy Gorgonzola, Grana Padano, Gruyère, Pecorino and ripened Ragusano (Table 7). It contributes positively to cheese flavour at low concentrations, while at high levels, at least in Gruyère cheese, a potato-like off-flavour is detectable (Rychlik & Bosset, 2001b).

Methanethiol is another important S-containing compound. It derives from methionine and may be a precursor for further sulphur compounds such as dimethyldisulphide (DMDS) and dimethyltrisulphide (DMTS) via oxidative reactions. Many micro-organisms are able to produce methanethiol from methionine, especially *P. camemberti*, *G. candidum* and *B. linens* (Jollivet, Chataud, Vayssier, Bensoussan, & Belin, 1994). Among these micro-organisms, coryneform bacteria, especially *B. linens*, are considered to be the key agents of sulphur-compound production in smear-ripened and mould-ripened cheeses such as Camembert (Molimard & Spinnler, 1996; McSweeney & Sousa, 2000). In varieties such as Cheddar, which lack a surface microflora, flavour is produced by starter and non-starter bacteria and their enzymes. In such cases, the origin of methanethiol is believed to be a chemical process (Kim & Olson, 1989). However, Urbach (1995) suggested that secondary flora, particularly in Cheddar and Emmental, are likely to be more important than chemical reactions in the formation of sulphur compounds. Methanethiol appears to be one of the characteristic flavour compounds of Camembert and regular/low fat Cheddar (Table 7). The typical flavour of Cheddar is produced by the interaction of methanethiol and an as yet unidentified acid fraction.

Dimethylsulphide (DMS), DMDS and DMTS are thought to be important contributors to cheese flavour. DMS is a product of the metabolism of propionic acid bacteria and is formed from methionine. It was listed as a main odorant of Camembert and Cheddar (regular and low fat) cheese types. In 8 and 12 months ripened Ragusano cheese the other S-compound, DMDS seems to become more important, while DMTS contributes

Table 7
N-containing compounds, pyrazines and S-containing compounds identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($\mu g\,kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($\mu g\,kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
N-compounds	2-Acetyl-1-pyrroline	Roasty	Camemb	1.4, 3.2	n 0.1 (SF oil)	7	AEDA/AECA/OAV	HVD	6, 7
	2-Acetyl-1-pyrroline	Roasty	Gru	FD 32			AEDA	HVD	14
	Indole	Mothball-like	Gru	FD 16			AEDA	HVD	14
	Indole	Stable, jasmine	Mozz Bov	*c* 54, % 1.8			Charm	VD	12
	Indole	Stable, jasmine	**Mozz WB**	*c* 291, % 10			Charm	VD	12
	Skatole		**Emm**	26, 40	n 15.6, rn 50 (SF oil)	21	AEDA/OAV	HVD	21, 22
	Skatole	Fecal	Ched RF//LF	3.8//5.2			AEDA/OAV	HVD	19
Pyrazines	2-Acetylpyrazine	Popcorn	Ched BF	FD 9			AEDA	HVT	16
	2,3-Dimethylpyrazine	Roasted nuts, coffee, peanut	Grana Pad 12 M	2			Charm	VD	11
	2-Ethyl-3,5-dimethylpyrazine	Earthy	**Gru**	0.7	n 2.2 (SF oil)		AEDA/OAV	HVD	14, 23
	3-Ethyl-2,5-dimethylpyrazine	Earthy, potato chips	Grana Pad 12 M	tr			Charm	VD	11
	3-Ethyl-2,6-dimethylpyrazine	Roasty	Pecorino 6 M	*c* 10, % 0.8			Charm	H-SPME	2
	3-Ethyl-2,6-dimethylpyrazine	Roasty	Ragus 4 M//8 M//12 M	*c* 29, % 2.2//*c* 30, % 1//*c* 12, % 0.5			Charm	H-SPME	2
	2-Isopropyl-3-methoxypyrazine	Earthy, soil	**Ched BF**	FD 729			AEDA	HVT	16
	3-Isopropyl-2-methoxypyrazine	Earthy, musty	Camemb	FD 32			AEDA	HVD	6
	2,3-Diethyl-5-methylpyrazine	Earthy	**Gru**	0.6	n 0.5 (SF oil)	24	AEDA/OAV	HVD	14, 23
	3,5-Diethyl-2-methylpyrazine	Potato	Grana Pad 12 M	2			Charm	VD	11
	2-Isobutyl-3-methoxypyrazine	Bell pepper-like	**Ched BF**	FD 9			AEDA	HVT	16
	2-*sec*-Butyl-3-methoxypyrazine		**Emm**	0.5, 1.0	n 0.5, rn 0.3 (SF oil)	21	AEDA/OAV	HVD	21, 22
S-compounds	**Methional** (3-methylthiopropanal)	Boiled potato-like	**Camemb**	27, 125	n 0.2, rn 0.05 (SF oil)	7	AEDA/AECA/GCO-H/OAV	HVD	6, 7
	Methional	Cooked milk, acrid, sulfur, oil, onions	Ched Ag	OP 9			AEDA	MD	17
	Methional	Baked potato	**Ched BF**	FD 729			AEDA	HVT	16
	Methional	Boiled potato-like	**Ched RF//LF**	3//5.9			AEDA/GCO-H/OAV	HVD	19
	Methional		**Emm**	15, 33	n 0.2, rn 0.05 (SF oil)	7	AEDA/OAV	HVD	21, 22
	Methional	Potato	**Goat BC**	+ + +			AEDA/Charm/Osme	VD	9
	Methional	Boiled potato	Gorg nat//**creamy**	tr//tr			Charm	VD	13

	Methional	Cooked milk	**Grana Pad 12 M**	3			Charm	VD	11
	Methional	Boiled potato	**Gru**	99	n 0.2 (SF oil)	21	AEDA/GCO-H/OAV	HVD	14, 23
	Methional	Potato	**Pecorino 6 M**	*c* 252, % 18.8			Charm	H-SPME	2
	Methional	Potato	Ragus 4 M//**8 M//12 M**	*c* 11, % 0.8//*c* 325, % 11.2// *c* 366, % 14.9			Charm	H-SPME	2
	Methional	Boiled vegetables	Roncal	*c* 8, % 0.4			Charm	SFE	8
	Methanethiol	Sulfurous	**Camemb**	260, 275	n 0.06, rn 0.34 (SF oil)	7	GCO-H/OAV	HVD	6, 7
	Methanethiol	Sulfury	**Ch RF//LF**	vol 10//vol 2.5			GCO-H	HVD	19
	Methanethiol	Sulfurous	**Gru**	700	n 0.06 (SF oil)	7	AEDA/GCO-H/OAV	HVD	14, 23
	Methylsulfide	Sulfurous, garlic-like	Camemb	250, 360	n 30, rn 42 (SF oil)	7	OAV/AEDA/GCO-H/OAV	HVD	6, 7
	Dimethylsulphide	Sulfurous	**Camemb**	250, 410	n 1.2, rn 2.3 (SF oil)	7	GCO-H/OAV	HVD	6, 7
	Dimethylsulphide	Pomegranate	Ched	OI 1			Osme	P & T	1
	Dimethylsulphide	Cabbage-like	**Ched RF//LF**	vol 10, vol 10			GCO-H	HVD	19
	Dimethylsulphide	Sulfurous	Gru	vol 1.25			GCO-H	HVD	14
	Dimethyldisulphide	Sulfurous, sour	Camemb	FD 4, vol 10			AEDA/GCO-H	HVD	6
	Dimethyldisulphide	Sulfurous	Gru	vol 10			GCO-H	HVD	14
	Dimethyldisulphide	Onion	Pecorino 6 M	*c* 49, % 3.7			Charm	H-SPME	2
	Dimethyldisulphide	Onion	Ragus 4 M, **8 M, 12 M**	*c* 69, % 5.1//*c* 347, % 11.9//*c* 286, % 11.7			Charm	H-SPME	2
	Dimethyltrisulphide	Vegetable-like, sulfurous	Camemb	8.4, 10.1	n 2.5, rn 4.2 (SF oil)	7	AEDA/AECA/GCO-H/OAV	HVD	6, 7
	Dimethyltrisulphide	Sulfurous, cabbage	Ched BF	FD 27			AEDA	HVT	16
	Dimethyltrisulphide	Putrid	Ched RF//LF	vol 5//vol 2.5			GCO-H	HVD	19
	Dimethyltrisulphide	Cabbage-like, sulfurous	**Gru**	136	n 2.5 (SF oil)	7	AEDA/AECA/GCO-H/OAV	HVD	14, 23
	Dimethyltrisulphide	Garlic	Pecorino 6 M	*c* 19, % 1.4			Charm	H-SPME	2
	Dimethyltrisulphide	Garlic	Ragus 8 M//12 M	*c* 11, % 0.4//*c* 58, % 2.4			Charm	H-SPME	2
	Dimethyltetrasulphide	Putrid	Ched RF//LF	vol 20 / vol 40			GCO-H	HVD	19
	Dimethyltetrasulphide	Cabbage-like	Gru	FD 128			AEDA	HVD	14
	Dimethylsulphone	Sulfurous, hot milk, burnt	Mozz Bov	*c* 32, % 1.1			Charm	VD	12
	Dimethylsulphone	Sulfurous, hot milk, burnt	Mozz WB	*c* 54, % 2			Charm	VD	12
N- & S-compounds	2-Acetylthiazoline	Roasty, corny	Ched RF//LF	FD 2//FD 8			AEDA	HVD	19

[b] Refer to footnote b in Tables 1 and 2.
[c] Refer to footnote c in Tables 1 and 2.
[d] Refer to footnote d in Tables 1 and 2.
[e] Refer to footnote e in Tables 1 and 2.
[f,i] For references 1–24 refer to footnotes f and i in Tables 1 and 2.
[g] Refer to footnote g in Tables 1 and 2.
[h] Refer to footnote h in Tables 1 and 2.

Table 8
Terpenes and miscellaneous compounds identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($\mu g\,kg^{-1}$) odour intensity, dilution factor[d]	Analytical method[e]	Extraction method[f]	Ref[g]
Terpenes	α-pinene	Pine, green	Ched Ag	OP 3	AEDA	MD	17
	L-Carvone	Herbaceous	Ragus 8 M	c 12, % 0.4	Charm	H-SPME	2
	Linalool	Sweet, floral	Ched BF	FD 9	AEDA	HVT	16
	Linalool	Orange, flower	Pecorino 6 M	c 38, % 2.8	Charm	H-SPME	2
	Geranyl acetate	Flower	Ragus 8 M	c 53, % 1.8	Charm	H-SPME	2
Miscellaneous compounds	Dodecane	Dirt	Ched	OI 3	Osme	P & T	1
	Trichloromethane (chloroform)	Hay	Ched	OI 0.5	Osme	P & T	1

[a] Refer to footnote a in Tables 1 and 2.
[b] Refer to footnote b in Tables 1 and 2.
[c] Refer to footnote c in Tables 1 and 2.
[d] Refer to footnote d in Tables 1 and 2.
[e] Refer to footnote g in Tables 1 and 2.
[f] Refer to footnote h in Tables 1 and 2.
[g] For references 1–17 refer to footnotes f and i in Tables 1 and 2.

significantly to the aroma of Gruyère cheese. DMTS is generally associated with odour notes of cooked cabbage, broccoli or cauliflower (Table 7).

3.4. Terpenes

Terpenes (Table 8) are important compounds in those cheeses which are manufactured in alpine regions in an artisanal way (Bugaud, Buchin, Coulon, Hauwuy, & Dupont, 2001; Bugaud, Buchin, Hauwuy, & Coulon, 2001). They originate from the plants that constitute the forage mixture of the pastures (Mariaca et al., 1997). They are then transferred to the milk of the grazing animals and ultimately to the cheese. Bosset, Bütikofer, Gauch, and Sieber (1994) compared 14 different types of Gruyère and Etivaz cheeses produced in alpine pastures with 20 others produced in the lowlands. They showed that alpine cheeses contained more terpenes than lowland cheeses. This finding is important for determining the geographical origin of a cheese type. It is also important for the producers who want to claim the particular naming rights for cheeses manufactured in a specified restricted area. Among the most frequently identified terpenes are α-pinene and linalool. These two terpenoids were found in aged Cheddar and Pecorino, respectively (Table 8). Linalool, together with terpineol and isoborneol, was also identified as a major terpene present in Vacherin (Dumont, Roget, Cerf, & Adda, 1974). This cheese has a ring of spruce wood around it during its ripening. This ring is thought to be responsible for the high level of terpenes in this cheese type. In general, though, the importance of terpenes in the formation of cheese flavour remains controversial. Therefore, it would be necessary to investigate further the relevance of these compounds by using a GC-O approach.

4. Acidic compounds

4.1. Phenolic compounds

Phenolic compounds (Table 9) appear to make a positive contribution to cheese flavour at about threshold concentration but tend towards an unpleasant note as their concentration increases. The sensory quality ranges from sharp, medicinal, sweet, aromatic to smoky, charred, caramel, unpleasant and "sheep-yard". Amongst these components, *p*-cresol (4-methylphenol) should be highlighted. This phenolic compound originates from tyrosine. Yeasts, micrococci and *B. linens* are capable of cleaving the side chain of tyrosine releasing the phenol (Parliment et al., 1982; Jollivet, Bézenger, Vayssier, & Belin, 1992). *p*-Cresol was listed as a main odorant of British farmhouse Cheddar and thought to be responsible for its "cowy-barny" note (Suriyaphan et al., 2001).

4.2. Free fatty acids (FFAs)

Fatty acids (Table 9) are important, or even predominant, components of the flavour of many cheese types. Fatty acids are not only aroma compounds by themselves, but also serve as precursors of methyl ketones, alcohols, lactones and esters. During cheese ripening, free fatty acids containing four or more carbon atoms may originate from lipolysis of milk fat or the breakdown of amino acids (Urbach, 1993). Lipolysis may be due to the action of the indigenous lipases of milk, in the case of cheese made from raw milk, or to the action of microbial lipases. Lactic acid bacteria present in starter cultures are generally only weakly lipolytic. However, most of the fatty acids, having between 4 and 20 carbon atoms, come from the lipolysis of triglycerides by moulds. A lower proportion of free fatty acids, having generally between 2 and 6 carbon atoms, originate from the degradation of lactose and amino acids. The shorter fatty acids can also be derived from ketones, esters and aldehydes by oxidation (Molimard & Spinnler, 1996). It is also important to note that the pH-value of the cheese affects the concentration of volatile fatty acids. Only the free, protonated form of fatty acids is odour-active and contributes to cheese flavour (Brennand, Ha, & Lindsay, 1989). These are mainly acids dissolved in the fat phase of the cheese.

In general, long-chain fatty acids (>12 carbon atoms) play a minor role in the flavour, given their relatively high perception thresholds. Short and moderate-chain, even numbered fatty acids (C_4–C_{12}) have much lower perception thresholds and each has a characteristic note. For example, ethanoic (acetic) acid and propanoic (propionic) acid have a typical vinegar odour. The former is a major odorant of Cheddar (aged, regular and low fat), Gruyère, Roncal (Table 9) and Emmental (Preininger, Warmke, & Grosch, 1996) cheese varieties. The latter is an important aroma component of aged Cheddar, Gruyère (Table 9) and Emmental (Preininger et al., 1996) cheese types.

Butanoic (butyric) acid has a rancid cheese-like odour and plays an important role in the flavour of many cheese types such as Camembert, Cheddar (aged, regular and low fat), Grana Padano, Gruyère, Pecorino, Ragusano and Roncal cheese (Table 9). However, large amounts of this volatile acid, which may originate from butyric acid fermentation, are undesirable. In the case of aged Cheddar, other straight-chain fatty acids such as pentanoic (valeric), hexanoic (caproic), decanoic (capric) and dodecanoic (lauric) acids also seem to contribute significantly to its aroma. Hexanoic acid is also a characteristic flavour component of Grana Padano and Roncal cheeses, while octanoic and decanoic acids are listed among the major odorants of the latter type of cheese (Table 9). From a sensory point of view, nonanoic acid provides a major contribution to the goaty flavour of goat cheese (Le Quéré, Septier, Demaizières, & Salles, 1996).

Branched-chain fatty acids are characteristic impact compounds of goat and sheep cheeses. Among them, 2- and 3-methylbutanoic acids are important components. They are related to an extensive breakdown of proteins. These two components are probably derived from isoleucine and leucine, respectively (Kuzdzal-Savoie, 1980). Together they impart "sweaty" and rancid cheese notes to Gruyère. Further, 3-methylbutanoic acid (isovaleric acid), with its rancid, cheesy, sweaty and putrid odour, probably contributes to the very-ripened-cheese aroma (Yvon & Rijnen, 2001). Another compound, 4-ethyloctanoic acid, is known to contribute to muttony, goaty flavour notes (Karl, Gutser, Dietrich, Maas, & Mosandl, 1994). As expected, this volatile acid plays an important role in the aroma of goat cheese and its significance is also suggested by its low perception threshold (Brennand et al., 1989).

Of the phenolic acids, phenylacetic acid with its honey-like note, seems to contribute significantly to the aroma profile of Gruyère cheese (Rychlik & Bosset, 2001a, b).

5. Discussion

5.1. Variability and limitations of GC-O data

Considering the data compiled in the nine tables, we notice a high degree of variability which makes the comparison of the results from different laboratories an extremely difficult, and most often, an impossible task to carry out. For example, we find different odour descriptors for the same aroma compound, various ways for evaluating the odour intensity as well as various extraction and GC-O methods. The variability found for the same type of cheese could be explained by the different extraction and GC-O methods used by the different research groups. Another source of variation that could explain the use of various odour descriptors for the same aroma compound could be the presence of different concentrations of such compound in different cheeses or a variable choice of descriptors adopted by the panelists. This very last consideration leads to another important aspect which has to be mentioned: the often problematic use of human subjects to do the sniffing. For example, a member of the sensory panel may be too highly or too little sensitive to certain classes of compounds (e.g. specific anosmia), thus introducing a bias which would make the GC-O results unreliable. Also inattention and non-continuous breathing (no odour perception while breathing out) could alter the

Table 9
Acidic compounds: phenolics and free fatty acids (FFAs) identified as odour-active compounds in different cheese types by GC-O

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($mg\ kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($mg\ kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
Phenolic compounds	Toluene	Nutty, bitter almond	Ched	OI 1			Osme	P & T	1
	4-Methylanisole	Gorgonzola cheese	Gorg nat//creamy	140//70	2 (water)	10	Charm/OAV	VD	13
	2-Methoxyphenol (guaiacol)	Spice, smoky	Ched BF	FD 27			AEDA	HVT	16
	Vanillin		Emm	FD <4, FD 32			AEDA	HVD	22
	Vanillin	Vanilla	Ragus 8 M//12 M	*c* 176, % 6//*c* 24, % 1			Charm	H-SPME	2
	4-Methylphenol (*p*-cresol)	Phenolic, medicinal	Camemb	FD 16			AEDA/AECA	HVD	6
	4-Methylphenol	Cowy, barny, medicine	**Ched BF**	FD 729			AEDA	HVT	16
	4-Methylphenol	Phenolic, musty, stable	Mozz Bov	*c* 43, % 1.5			Charm	VD	12
	4-Methylphenol	Phenolic, musty, stable	Mozz WB	*c* 37, % 1.3			Charm	VD	12
Straight-chain FFAs	Ethanoic acid (acetic acid)		Camemb	58.8, 91.8			AEDA/OAV	HVD	6, 7
	Ethanoic acid	Peppers, green, fruity floral	**Ched Ag**	OP 27			AEDA	MD	17
	Ethanoic acid	Vineger	Ched BF	FD 81			AEDA	HVT	16
	Ethanoic acid	Sour	**Ched RF//LF**	96.2//121			AEDA/GCO-H/OAV	HVD	19
	Ethanoic acid	"Stechend, nach Essig" (pungent, vineger-like)	Emm	FD <1			AEDA	HVD	31
	Ethanoic acid	Acetic, sour	Grana Pad 12 M	*c* 6, % 2.3			Charm	VD	11
	Ethanoic acid		**Gru**	298	rn 54 (water)	32	OAV	HVD	23
	Ethanoic acid	Acetic	Ragus 8 M	*c* 2, % 0.1			Charm	H-SPME	2
	Ethanoic acid	Vinegar	**Roncal**	*c* 4, % 9.7			Charm	H-SPME	2
	Propanoic acid (propionic acid)		Camemb	13.3, 25.9			AEDA/OAV	HVD	6, 7
	Propanoic acid	Gas, burnt, sulfuor, cloves, solvent	**Ched Ag**	OP 81			AEDA	MD	17
	Propanoic acid	"Stechend, süßlich" (pungent, sweetish)	Emm	FD 1			AEDA	HVD	31
	Propanoic acid	Fruity, pungent	**Gru**	87	rn 30 (water)	32	AEDA/OAV	HVD	14, 23
	Butanoic acid (butyric acid)		**Camemb**	121.6, 130.4			AEDA/AECA/OAV	HVD	6, 7
	Butanoic acid	Nacho cheese, cheese, toasted cheese	**Ched Ag**	OP 729			AEDA	MD	17
	Butanoic acid	Fecal, cheesy	Ched BF	FD 243			AEDA	HVT	16
	Butanoic acid	Sweet, sweaty	**Ched RF//LF**	10.1//16.6			AEDA/OAV	HVD	19
	Butanoic acid	"Ranzig" (rancid)	Emm	FD 1			AEDA	HVD	31
	Butanoic acid	Cheese, rancid, sour	**Grana Pad 12 M**	*c* 131, % 50			Charm	VD	11

Butanoic acid	Cheese	Goat BC	+			AEDA/Charm/Osme	VD	9
Butanoic acid	Sweaty	**Gru**	97	rn 18 (water)	32	AEDA/OAV	HVD	14, 23
Butanoic acid	Dirty sock	**Pecorino 6 M**	*c* 340, % 25.4			Charm	H-SPME	2
Butanoic acid	Dirty sock	**Ragus 8 M//12 M**	*c* 271, % 9.3//*c* 708, % 28.9			Charm	H-SPME	2
Butanoic acid	Strong cheese, manure, ripe cheese	**Roncal**	*c* 32, % 16			Charm	SFE	8
Pentanoic acid (valeric acid)		Camemb	FD 16			AEDA	HVD	6
Pentanoic acid	Rain, wood, vegetable, spicy, nutty, grain	**Ched Ag**	OP 27			AEDA	MD	17
Pentanoic acid	Swiss cheese	Ched BF	FD 27			AEDA	HVT	16
Pentanoic acid	Stable, sweaty, bedsteam, sheep, goat	Grana Pad 12 M	*c* 4, % 1.5			Charm	VD	11
Hexanoic acid (caproic acid)		Camemb	58.5, 70			AEDA/OAV	HVD	6, 7
Hexanoic acid	Bad breath, popcorn, goaty, free fatty acid	**Ched Ag**	OP 81			AEDA	MD	17
Hexanoic acid	Cheese rind, grated cheese, sweaty	**Grana Pad 12 M**	*c* 87, % 33.2			Charm	VD	11
Hexanoic acid	Goat	Goat BC	70, +			AEDA/Charm/Osme	VD	8
Hexanoic acid	Goat-like	Gru	28	rn 81 (water)	32	AEDA/OAV	HVD	14, 23
Hexanoic acid	Cheese-making, cheese	**Roncal**	*c* 32, % 10.3			Charm	SFE	8
Heptanoic acid (enanthic acid)	Fatty, rancid	Grana Pad 12 M	*c* 5, % 1.9			Charm	VD	11
Heptanoic acid	Rancid	Goat BC	ne			AEDA	VD	9
Octanoic acid (caprylic acid)		Camemb	62.2, 70.1			AEDA/OAV	HVD	6, 7
Octanoic acid	Body odour, sweat	Ched BF	FD 81			AEDA	HVT	16
Octanoic acid	Fatty, rancid	Grana Pad 12 M	*c* 5, % 1.9			Charm	VD	11
Octanoic acid	Rancid, pungent	Goat BC	113, +			AEDA/Charm/Osme	VD	9
Octanoic acid	Cheese, cheese rind	**Roncal**	*c* 8, % 24			Charm	SFE	8
Nonanoic acid (pelargonic acid)	Goat	**Goat BC**	0.81, + +			AEDA/Charm/Osme	VD	9
Decanoic acid (capric acid)		Camemb	196.4, 218.8			AEDA/OAV		
Decanoic acid	Warm, stale butter, sour fruit	**Ched Ag**	OP 9			AEDA	MD	17
Decanoic acid	Grassy, fatty, sour	Grana Pad 12 M	*c* 12, % 4.6			Charm		
Decanoic acid	Goat	Goat BC	28, +			AEDA/Charm/Osme	VD	9
Decanoic acid	Cheese, milk, aged cheese	**Roncal**	*c* 8, % 11.6			Charm		
Dodecanoic acid (lauric acid)		Camemb	FD 4			AEDA	HVD	6
Dodecanoic acid	Soapy	**Ched Ag**	OP 9			AEDA	MD	17
Dodecanoic acid	Homemade soap, hot milk, rind	Roncal	*c* 32, % 8.2			Charm	SFE	8

(*continued on next page*)

Table 9 (*continued*)

Functional group	Chemical compound[a]	Odour descriptor(s)[b]	Cheese type[c]	Concentration ($mg\ kg^{-1}$) odour intensity, dilution factor[d]	Thresholds ($mg\ kg^{-1}$)[e]	Ref[f]	Analytical method[g]	Extraction method[h]	Ref[i]
	Tetradecanoic acid	Sweat, animal	Roncal	*c* 8, % 1.6			Charm	SFE	8
Branched FFAs	Methylpropionic acid	Sweaty, rancid	Gru	41	rn 88 (water)	32	AEDA/OAV	HVD	14, 23
	2-Methylpropanoic acid (isobutyric acid)		Camemb	FD 16			AEDA	HVD	6
	2-Methylpropanoic acid	Cheese, rancid butter	Grana Pad 12 M	*c* 6, % 2.3			Charm	VD	11
	2- & 3-Methylbutanoic acid	Sweaty	**Gru**	81	rn 10 (water)	32	AEDA/OAV	HVD	14, 23
	3-Methylbutanoic acid (isovaleric acid)		**Camemb**	3.4, 4.5			AEDA/AECA/OAV	HVD	6, 7
	3-Methylbutanoic acid	Swiss cheese	Ched BF	FD 243			AEDA		
	3-Methylbutanoic acid	"Süßlich, schweißig" (sweetish, sweaty)	Emm	FD 5			AEDA	HVD	31
	3-Methylbutanoic acid	Cheese rind, rancid	Grana Pad 12 M	*c* 6, % 2.3			Charm		
	3-Methylbutanoic acid	Cheese	**Goat BC**	+ +			AEDA/Charm/Osme	VD	9
	3-Methylbutanoic acid	Roncal cheese	Roncal	*c* 2, % 2.6					
	4-Methyloctanoic acid	Goat	Goat BC	0.26, +	0.6	29	AEDA/Charm/Osme	VD	9
	4-Ethyloctanoic acid	Goat	**Goat BC**	0.03, + + +	0.006	29	AEDA/Charm/Osme	VD	9
Aromatic FFAs	Phenylacetic acid	Rosy	Ched BF	FD 81			AEDA	HVT	16
	Phenylacetic acid	Honey-like	**Gru**	7.3	n 0.19 (SF oil)	30	AEDA/OAV	HVD	14, 23
	Phenylpropanoic acid	Flowery	Gru	FD 128			AEDA	HVD	14, 23

[a] Refer to footnote a in Tables 1 and 2.
[b] Refer to footnote b in Tables 1 and 2.
[c] Refer to footnote c in Tables 1 and 2.
[d] Refer to footnote d in Tables 1 and 2.
[e] Refer to footnote e in Tables 1 and 2.
[f] Threshold reference.
[g] Refer to footnote g in Tables 1 and 2.
[h] Refer to footnote h in Tables 1 and 2.
[i] Reference numbers are as follows (for references 1–23 refer to footnotes f and i in Tables 1–4): (29) Brennand, Ha, and Lindsay (1989); (30) Kerscher (2000); (31) Preininger (1995); (32) Warmke, Belitz, and Grosch (1996).

aroma perception of the panellist. Further, only small numbers of evaluators are generally employed for the sensory evaluation and this could introduce statistical errors.

From the foregoing, we can conclude that GC-O data, due to their sensory nature, cannot be presented and compared with the same precision as other chemical data. Unlike RI values and mass spectra, GC-O data cannot be precisely determined and, therefore, they lack the equivalent comparable accuracy and reproducibility, although, with the necessary precautions (e.g. the careful selection and training of the assessors), their variability can be considerably reduced.

5.2. Methodological aspects and limitations

It was found, by means of GC-O analysis, that only a few of the great number of volatile compounds from a cheese contribute significantly to its flavour. Moreover, these few odour-active components seem to depend rather more on the extraction method used than on the cheese type itself, at least from a qualitative point of view. The main differences characterising the various cheese varieties are probably much more related to quantitative differences. In general, as pointed out by Bosset and Gauch (1993), the flavour of cheese seems not to depend on the concentration of any particular compound itself, but on a critical balance or "weighted ratio" of all components present. This conclusion supports the component balance theory already stated by Kosikowski and Mocquot (1958) for Cheddar cheese. This consideration leads to a difficult question: which extraction method allows us to perceive the most representative odour mixture? Each extraction technique has advantages and disadvantages. Direct extraction methods are generally very rapid but limited to samples with low fat content. They imply the use of organic solvents which may be toxic and lead to contaminations and/or chromatographic peak overlapping. SFE methods using CO_2, avoid the problems associated with the use of organic solvents but are also limited in their application to samples with low fat content, because of the simultaneous extraction of mono-, di- and triglycerides. Steam distillation techniques, followed by a further extraction and concentration with an organic solvent, are widely used and very popular. However, they also suffer from several problems: low recoveries of highly volatile components and/or masking of peaks by the solvent peak, introduction of contaminants with the solvent and possible thermal degradation of labile compounds if steam distillation is not performed under reduced pressure. High-vacuum distillation methods prevent or limit thermal degradation by working at ambient or sub-ambient temperatures, but they usually require large amounts of samples and are very time-consuming. Further, static headspace techniques are limited to the most volatile compounds, the fugacity of which must be identical in the gas and in the sample phase (thermodynamic equilibrium). Dynamic headspace techniques make it possible to obtain more concentrated extracts but, if they are used only for a short time they tend, as with the static headspace techniques, to selectively enrich the most volatile components. On the other hand, using prolonged extractions (e.g. hours) may overestimate compounds with low volatility.

The problems related to each extraction method have been extensively discussed by Etiévant and co-workers (1994) and Mariaca and Bosset (1997). An elegant solution has been proposed by Chaintreau, Grade, and Muñoz-Box (1995). These authors suggest that one should analyse by GC-O the odour-active compounds present within about 150 mL (the volume equivalent to one inspiration or one "sniffing") of the static headspace, in equilibrium with the sample, by trapping them slowly enough to avoid any equilibrium displacement during this trapping. This approach is an interesting compromise between a static and a dynamic analysis, which combines the advantages of the two methods and limits their relative drawbacks. Another alternative solution to overcome the limitations of each single extraction method, at least theoretically, would be to perform several different extractions for each sample and compare the results obtained.

Apart from the extraction method itself, the techniques used to generate the GC-O data are also often questionable. This topic has been reviewed by Mistry, Reineccius, and Olson (1997) and by Blank (1997). The procedures based on dilution series, such as the AEDA or the CharmAnalysis, are extremely laborious and time consuming. It is, therefore, difficult to perform duplicate and triplicate analyses or to check the reproducibility among different GC-O users. Human fatigue also becomes a major concern. Both AEDA and CharmAnalysis can be regarded as screening methods and do not consider the physical factors of the food matrix or the physiological processes of aroma perception. The Osme type of analysis differs from the previous two methods in that only one concentration of the extract is evaluated. No dilution series is prepared, hence results obtained by Osme are not based on odour detection thresholds. The collected data could be analysed by common statistical methods but, so far, statistical analysis has not been applied to this kind of approach. (S)NIF techniques, instead, are based on detection frequencies, rather than on perceived intensity or successive dilutions as used in other procedures. Due to the greater number (minimum 6) of panelists employed, they seem to provide more repeatable and reproducible results (Pollien et al., 1997).

A valuable approach for verifying the representativeness of the aroma compounds identified by GC-O are aroma-recombination studies. Their principle is to reconstitute a mixture of key aroma components within a flavour-neutral matrix, such as an unripe cheese of the type Mozzarella, and to analyse it using a sensory panel (Preininger et al., 1996; Kubícková & Grosch, 1998a; Rychlik & Bosset, 2001b).

5.3. Metabolic origin of aroma compounds

From a metabolic point of view, the identification of key aroma components in various cheeses shows that amino acid degradation is a major process for aroma formation in cheese. Aromatic amino acids (phenylalanine, tyrosine, tryptophan), branched-chain amino acids (leucine, isoleucine and valine) and methionine are the major precursors of these aroma compounds (Yvon & Rijnen, 2001). In addition, enzymatic hydrolysis of triglycerides to fatty acids and glycerol, mono- or diglycerides (lipolysis) is essential to flavour development in many cheese varieties (McSweeney & Sousa, 2000).

6. Conclusions

GC-O analysis is a useful method for analysing aroma compounds in cheese. However, special care and attention must be taken to ensure that data are collected in a reproducible and robust fashion. The importance of all aspects in the GC-O approach must be considered, including selection of software and hardware components, sample handling, extraction of volatiles, selection and testing of analysis and implementation of GC-MS to identify compounds of interest as evaluated by GC-O analysis. Only when all these aspects are carefully considered and dealt with, can this method provide useful information to food analysts. In most cases, though, final conclusions about the sensory relevance of volatile compounds cannot be drawn from GC-O data and further research is necessary to achieve a thorough understanding of aroma chemistry of cheese. Much more work should be done especially in the standardisation of procedures to be able to reduce variability and compare results from different laboratories in a more efficient way.

Acknowledgements

We are grateful to Dr. B. Jeangros (RAC, Changins-Nyon) for the logistical support and his kind hospitality during the stage. We thank Mrs. G. Urbach (South Caulfield, Australia) and Dr. A. Chaintreau (Firmenich, Geneva) for reviewing the manuscript, as well as to Mrs. B. Walther (FAM, Liebefeld-Bern) for her help in searching bibliographic references in international databases.

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