Indoor Air Quality Assessment Based on Human Physiology – Part 1. New Criteria Proposal

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Human physiology research makes evident that the Weber-Fechner law applies not only to noise perception but also to the perception of other environmental components. Based on this fact, new decibel units for odor component representing indoor air quality in majority locations have been proposed: decicarbdiox dCd (for carbon dioxide CO_2) and decitvoc dTv (for total volatile organic compound TVOC). Equations of these new units have been proved by application of a) experimental relationships between odor intensity (representing odor perception by the human body) and odor concentrations of CO_2 and TVOC, b) individually measured CO_2 and TVOC levels (concentrations) – from these new decibel units can be calculated and their values compared with decibel units of noise measured in the same locations. The undoubted benefit of using the decibel scale is that it gives much better approximation to human perception of odor intensity compared to the CO_2 and TVOC concentration scales.

Keywords: indoor air quality, odors, air changes estimation.

1 Introduction: the "indoor quality" concept

The quality of indoor air is affected by all components of the environment, the so-called constituents of the microclimate (see Fig. 1.1, Table 1.1) [27]. Existence of the individual components is obvious from: (1) the differential equation of the environment (only agents creating exposing flows in the human organism can be taken into account), (b) the stress theory according to Selye (each constituent is created only by those agents or complexes of agents creating one type of stress in the human body, see [27]).
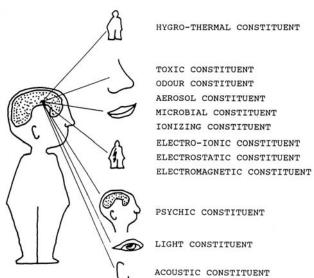

Fig. 1.1: Types of constituent

Air quality is thus dependent on its temperature and relative humidity, the concentrations of odors and toxic materials, the number of aerosols and microbes in the air, contamination by radioactive gases, static electricity and the numbers of negative and positive ions in the air.

The impact of each of these factors depends on the magnitude of the stimulus. Taking into account air quality only,

Table 1.1: Common environmental agents and corresponding microclimate types

AGENTS		MICROCLIMATE	
MATERIAL	TOXIC SOLIDS SOLID AEROSOLS MICRO-ORGANISMUS TOXIC LIQUIDS LIQUID AEROSOLS TOXIC GASES ODOURS AIR (ITS MOVEMENT) SPACE (ITS COLOURNESS) MAN (AS AN OBJECT) WATER VAPOURS	AEROSOL MICROBIAL AEROSOL TOXIC ODOUR	"PSYCHIC MICROCLIMATE"

ENERGETIC	HEAT CONVECTION
	         CONDUCTION
	         EVAPORATION
	         RESPIRATION
	         RADIATION
	LIGHT
	UV RADIATION
	LASER RADIATION
	MICROWAVE RADIATION
	(RADAR)
	IONIZING RADIATION
	IONS IN SURROUNDING AIR
	STATIC ELECTRICITY
	SOUND
	FORCE FIELD
	   (GRAVITATION)
	VIBRATION
		HYGRO-THERMAL
		
		ELECTRO-DYNAMIC
		
		ELECTRO-IONIC
		ELECTROSTATIC
		ACOUSTIC	

i.e. the chemical components of indoor air, pleasant or unpleasant odors dominate the perception of the environment by the occupant, if there are no significant indoor sources. That is why odors have become the criteria for assessing overall air quality [39], [41].

However, we always have to remember that it is solely the odor microclimate that we are evaluating and not the overall indoor air quality. This means that, if a significant source is present, e.g. water vapour or carbon monoxide, the hygrothermal or the toxic constituent has to be evaluated according to its own criteria (e.g. acceptable relative humidity of the air or acceptable carbon monoxide concentration).

Simultaneously, the increasing requirements for indoor air quality in buildings need more exact criteria in order to ascertain the real condition of the environment and to allow

better optimization of its level (see [29], [30]), to remove "sick building" symptoms, i.e. to get the real comfort within a building.

Human physiology research makes evident that the Weber-Fechner law applies not only to noise perception but also to the perception of other environmental components. According to this law human body response (R) is proportionate to the logarithm of the stimulus (S; k is a constant):

$$R = k \log S . \qquad (1)$$

Applied to acoustic component of the environment

$$L_P = SPL = 20 \log \frac{P}{P_0} \ [\text{dB}], \qquad (2)$$

where $L_P = SPL$ = sound pressure level [dB]; P = acoustic pressure (when measuring the RMS value, i.e. the square root of the arithmetic average of a set of squared instantaneous values); P_0 = acoustic pressure at the threshold of hearing (for air $P_0 = 20 \ \mu\text{Pa}$).

Analogical relationship could be supposed for odor component of environment [27] which determines the necessary indoor air exchange (by which unpleasant odors should be removed, the toxic gases removal by ventilation usually highly exceeds ordinary requirements and must be solved separately):

$$L_{\text{odor}} = k_{\text{odor}} \log(\rho/\rho_0) \ [\text{dB}], \qquad (3)$$

where L_{odor} represents the odor concentration level in dB (the value representing the human response, i.e. odor perception [dB]), ρ represents the odor concentration in a building interior [$\text{g}\cdot\text{m}^{-3}$], [ppm], ρ_0 represents the odor concentration threshold value [$\text{g}\cdot\text{m}^{-3}$], [ppm].

The psycho-physical scale by Jaglou (the scale of perceived odors) could be applied to odor concentration levels [18]. In relationship to the percentage of dissatisfied (PD) its experimentally formed course is presented in Fig. 1.2.
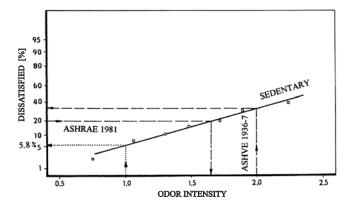

Fig. 1.2: The relationship between odor intensity (Yaglou's psycho-physical scale) and the percentage of dissatisfied sedentary subjects during light activity (smoking not permitted) [18]

It is a logarithmic function (see equation (1)) that proves the logarithmic form of equation (3).

The odor indoor air quality, decisive for air exchange, is dominantly determined by two odor substances: carbon dioxide CO_2, which cannot be neglected in rooms occupied by a higher number of people (it is produced by respiration) and the complex of volatile organic compounds (VOC) produced by the majority of upholstery and building materials.

The following equations could be written for CO_2 and TVOC:

$$L_{\text{odor } CO_2} = k_{\text{odor } CO_2} \log\left(\rho_{CO_2}/\rho_{0\,CO_2}\right) \ [\text{dB } CO_2], \qquad (4)$$

$$L_{\text{odor TVOC}} = k_{\text{odor TVOC}} \log\left(\rho_{\text{TVOC}}/\rho_{0\,\text{TVOC}}\right) [\text{dB TVOC}], \qquad (5)$$

where ρ_{CO_2} and ρ_{TVOC} represent the concentrations of CO_2 and TVOC.

Even though these equations (4, 5) look very promising from the physiological point of view, they must be experimentally proved. Furthermore, at least two points are necessary for each equation: (1) minimum threshold value, i.e. the weakest odor that can be detected (odor tresholds are statistically determined points usually defined as the point at which 50 % of a given population will perceive on odor" [24]), (2) any second point can be chosen. We prefer the maximum threshold (limit) value, i.e. the beginning of the toxic range.

The weakest odor that the smell organ of a healthy human can register has an intensity of l, according to the Yaglou psycho-physical scale [18], and corresponds approximately to a percentage dissatisfaction (PD) of 5.8 % (see Fig. 1.2). If we respect the similarity theory (see [21]), according to which analogous phenomena are governed by the same laws (e.g., concerning the perception of noise, odor etc. with intensity as a logarithmic function), then the corresponding minimal value for thermal comfort, as defined by Fanger [16], is 5 which is not too dissimilar from 5.8 for Yaglou's odor value, taking into account the demanding nature of the experimental procedure.

There is a good collection of experimental values in literature, therefore it has not been necessary to rely on our own measurements; even complete curves (see for example Fig. 1.2) are available.

2 Carbon dioxide

For a long time, the odor constituent has been evaluated on the basis of CO_2 concentration and its limit value of 1000 ppm, introduced by von Pettenkoffer (see [42]), was used to determine the minimum amount of fresh air (25 $\text{m}^3\cdot\text{h}^{-1}$ per person). CO_2 is the most important biologically active agent whose production is proportional to human metabolic ratio [24]. In practice, monitoring CO_2 levels for the purpose of controlling fresh air supply has proved satisfactory for lecture theatres, halls, cinemas, theatres and similar spaces where the load imposed by occupants can vary rapidly.

In order to prove the equation (4), another experimental relationship besides the experimental relationship presented in Fig. 1.2 must be available: namely, the relationship between PD and CO_2 concentration. This is presented in Fig. 1.3.

Now we are able to shape the equation (4). The first point, the minimum threshold value for CO_2 can be taken as 5.8 % dissatisfaction (Yaglou psycho-physical scale: 1), which is 485 ppm, i.e. 875 $\text{mg}\cdot\text{m}^{-3}$ Figs. 1.2 and 1.3 [15]. The second point used was the short-term exposure limit, which is the beginning of the toxic range, i.e. 15000 ppm. This is based on [22] from the Health and Safety Executive (HSE) Occupational Exposure Limits of Great Britain.
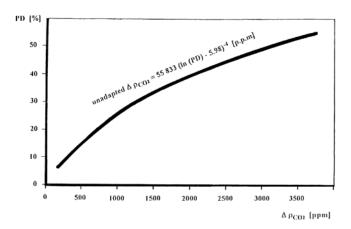
Fig. 1.3: The percentage of dissatisfied sedentary subjects as a function of the carbon dioxide concentration above outdoors

So we are able to formulate the equation for odor level:

$$L_{\text{odor CO}_2} = 90 \log \frac{\rho_{i\text{CO}_2}[\text{ppm}]}{485} [\text{decicarbdiox}, \text{dCd}] \qquad (6)$$

$$\left(k_{\text{odor CO}_2} \log(15000/485) = 135 \Rightarrow k_{\text{odor CO}_2} = 90 \right)$$

or

$$L_{\text{odor CO}_2} = 90 \log \frac{\rho_{i\text{CO}_2}[\text{mg} \cdot \text{m}^{-3}]}{875} [\text{decicarbdiox}, \text{dCd}] \quad (6a)$$

where decicarbdiox, dCd, is a new decibel unit for odor level (*deci*bel *carb*on *diox*ide) caused by CO_2 production by humans, $\rho_{i\text{CO}_2}$ is indoor air concentration, $k_{\text{odor CO}_2}$ is constant.

Besides experimental functions already applied to equation (4), a lot of individually measured CO_2 levels from various locations (Tables 1.2 and 1.3, Fig. 1.4) are available for the verification of the equation (4).

New decibel units dCd can be calculated from the measured CO_2 concentrations and their values can be compared

Table 1.2: Measured CO_2 levels in various locations [23]

Sample	Mean, dCd / ppm		Range, dCd / ppm		Study
	S	NS	S	NS	
Public places					
39 schools (NS)	– –	28 dCd 990 ppm	– –	−5 to 68 425–2800	Smedje et al 1994
10 schools (NS)	– –	38 1300	– –	– –	Thorstensen et al 1990
14 town halls (S)	20 800	– –	1 to 38 500–1300	– –	Skov, Valbjorn 1987
5 office buildings (S)	– –	– –	<26 <950	– –	Palonen, Sepanen, 1990
4 office buildings (S)	20 800	– –	−8 to 38 400–1300	– –	Loewenstein 1989
26 office buildings (S)	11 639.4	– –	−13 to 52 350–1850	– –	Reynolds et al 1990
10 kindergarten	– –	27 962.7	– –	25 to 66 915–2590	Piade et al 1988
1 office building (S)	−6 420	– –	– –	– –	Jaakola et al 1990
10 offices (5 S, 5 NS assumed)	8 590	4 533	– –	– –	Proctor et al 1989
1 office	– –	– –	8 to 13 600–675	– –	Berglund et al 1982
1 library	– –	16 731.5	– –	– –	Berglund et al 1988
9 office buildings (S)	15 710.6	– –	– –	– –	Jones 1980
Homes[a]					
10 homes and apartments	14 692		−1 to 40 470–1360		van der Wal et al 1990

Table 1.2: Measured CO_2 levels in various locations [23] (continue)

Sample	Mean, dCd / ppm		Range, dCd / ppm		Study
	S	NS	S	NS	
18 homes	6 570		−13 to 24 350–900		Keskinen, Graeffe 1989
57 homes	16 730.5		– –		van Dangen, van der Wal 1990
living room b.r.	29 1024		– –		Op't Veld, Slijpen 1993
living room a.r.	23 882		– –		Op't Veld, Slijpen 1993
kitchen b.r.	29 1013		– –		Op't Veld, Slijpen 1993
kitchen a.r.	21 836		– –		Op't Veld, Slijpen 1993
bedroom b.r.	25 927		– –		Op't Veld, Slijpen 1993
bedroom a.r.	13 672		– –		Op't Veld, Slijpen 1993

S – smoking, NS – nonsmoking, a.r. – after renovation, b.r. – before renovation, negative values of dCd – measuring methods allow estimating of values below the detection threshold, [a]no distiction made between smoking/non-smoking.

Table 1.3: Measured indoor quality parameters before and after renovation (mean values and standard deviations, $n = 16$) [38]

		Before renovation			After renovation			WHO 1987 guideline values
		living room	kitchen	bedrooms	living room	kitchen	bedrooms	
(dCd)	mean	29	29	25	23	21	13	35
CO_2	mean	1024	1013	927	882	836	672	1200
(ppm)	std	184	277	193	160	122	148	
CO	mean	3.9	4.3	4.2	2.2	2.0	1.4	10 (8 h)
$(mg \cdot m^{-3})$	std	0.4	0.2	1.6	1.0	0.5	0.5	
CH_2O^*	mean	665	577	530	405	357	231	120 (0.5 h)
$(\mu g \cdot m^{-3})$	std	214	51	234	167	153	188	
TVOC (ref CH_4)	mean	–	–	–	4.5	4.1	2.9	–
$(mg \cdot m^{-3})$	std	–	–	–	1.0	1.0	1.0	
NO_2	mean	84	160	30	30	34	16	150
$(\mu g \cdot m^{-3})$	std	40	127	9	16	14	3	(24 h)
Resp.dust	mean	30	–	–	30	–	–	70
$(\mu g \cdot m^{-3})$	std	16	–	–	15	–	–	(PM10 24 h)
RH(%)	mean	42	41	57	45	44	45	(30–70) %
	std	4	6	9	4	3	4	

* including a.o. other aldehydes, C_5H_{12}, C_6H_{14}
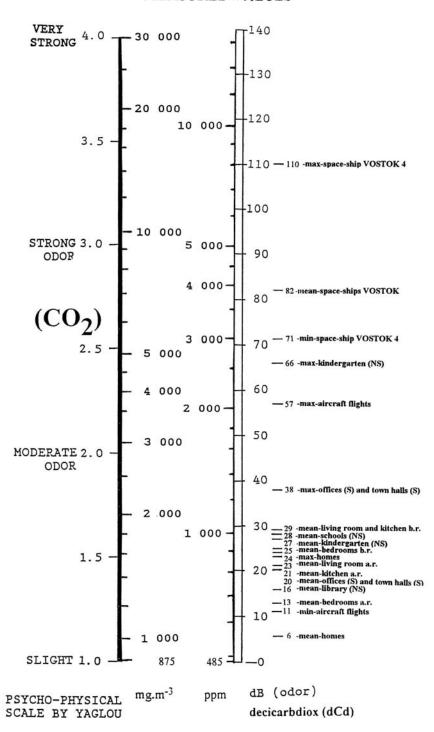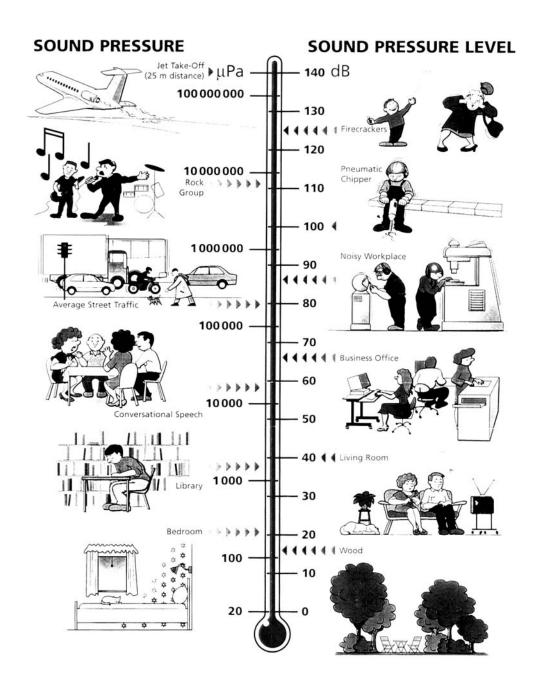
MEASURED VALUES

Fig. 1.4: The measured CO_2 levels in various buildings (see Table 1.2); the psychophysical scale slightly modified by Fanger (1988), S – smoking, NS – nonsmoking, a.r. – after renovation, b.r. – before renovation

with decibel units for noise measured in the same locations (Fig. 1.5). A perfect agreement is evident.

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3 Volatile organic compounds

Although CO_2 is a good indicator of the perceived air quality by sedentary persons, it is frequently also an unsuitable indicator: it does not represent further perceived sources of air contamination, such as building materials and fittings, especially carpets and other floor covering materials, producing VOC.

This was why Fanger [17] proposed a new system based on the units of the "olf" and "decipol". It was presented in a number of international periodicals and publications and in 1992 became the EU recommended method of evaluating indoor air quality (EUR 14449 EN, 1992). It was not, however, accepted for the BSR/ASHRAE Standard 62-1989 R (1989). There are certain obvious problems with this system, as were analysed by Oseland [39], Jokl et al [28] and especially by Parine [41].

Fanger's system, as used in the EC standard, is based, rather than on CO_2, on a new criterion: the total of all volatile organic compounds (TVOC) produced by humans and especially by building materials, furniture and other fittings. TVOC is also used for outside air quality as used for ventilation purposes, especially in areas with sources of contamination (chemical and other factories).

TVOC is defined by the World Health Organisation (WHO) as a set of agents (toluene, xylene, pinene, 2-(2et-oxyetoxy), ethanol etc.) with a melting point below room temperature and a boiling point in the range 50–260 °C. More detailed definitions also exist.

Humans sense TVOC by means of olfactory (smell) sensors (see [27]). Adaptation during the course of exposure is small. The response of the human organism to indoor TVOC has been classified as acute sensing of the environment, acute

or sub-acute inflammation of the skin or mucous membranes, or a sub-acute and mild stress reaction [15].

In order to prove the equation (5), besides the experimental relationship presented in Fig. 1.2, another experimental relationship must be available: namely, the relationship between PD and TVOC concentrations. It is presented in Fig. 1.6.
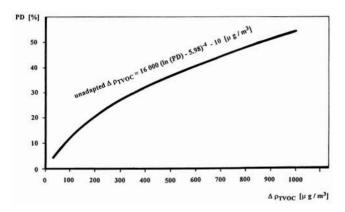

Fig. 1.6: The percentage of dissatisfied sedentary subjects as a function of the total volatile organic compound concentration (TVOC) above outdoors

Now we are able to shape the equation (5).

The first point, the minimum threshold value for TVOC, can be taken as 5.8 % dissatisfaction (Yaglou psychophysical scale: 1) which is 50 $\mu g \cdot m^{-3}$, see Fig. 1.6 (adapted from Fig. 1.2 in EUR 14449 EN, see [30]).

The second point used was the short-term exposure limit, which is the beginning of the toxic range, i.e. 25000 $\mu g\ m^{-3}$, which has been estimated by Molhave [36].

So we are able to formulate the equation for odor level:

$$L_{\text{odor TVOC}} = 50 \log \frac{\rho_{i\text{TVOC}}}{50}\ \ [\text{decitvox, dTV}] \tag{7}$$

$$(k_{\text{odor TVOC}} \log(25000/50) = 135 \Rightarrow k_{\text{odor TVOC}} = 50)$$

where decitvoc, dTv, is a new decibel unit for odor level caused by TVOC release from building materials and other sources (*deci*bel TVOC), $k_{\text{odor TVOC}}$ is a constant.

Besides experimental functions already applied to equation (5), a lot of individually measured TVOC levels from various locations (Tables 1.3 and 1.4, Fig. 1.7) are available for the verification of the equation (5).

New decibel units dTv can be calculated from the measured TVOC concentrations and their values can be compared with decibel units for noise measured in the same locations (Fig. 1.5). A perfect agreement is evident.
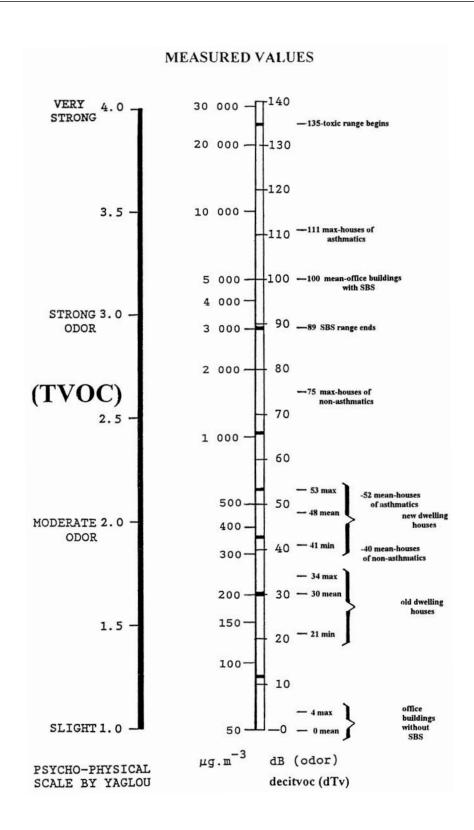
4 Conclusions

1. The undoubted benefit of using the decibel scale is that it gives a much better approximation to human preception of odor intensity compared to the CO_2 and TVOC concentration scales. This is because the human olfactory organ (see [27]) reacts to a logarithmic change in level

Table 1.4: Measured TVOC values in various locations

Sample	TVOC [$\mu g \cdot m^{-3}$]			Odor level [dTv]			Study
	min	mean	max	min	mean	max	
Living rooms and bedrooms							
old houses	130	200	240	21	30	34	Brown, Crump 1993
new houses	330	460	580	41	48	53	
non-asthmatics	72	320	1600	8	40	75	Nordbäck et al 1993
asthmatics	67	540	8300	6	52	111	
Office buildings							
a) without SBS							
during working hours	43	51	61	−3*	0	4	Ekberg 1993
during night-time	37	44	49	−6*	−3*	0	
during weekend	37	–	–	−6*	–	–	
b) with SBS							
(liquid process photo copiers)	–	5000	90000	–	100	163	Broder et al 1993

SBS = Sick Building Syndrome
* Measuring methods allow to estimate values under the detection threshold

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MEASURED VALUES

which corresponds to the decibel scale, where a change of 1 dB is approximately the same relative change everywhere on the scale.

2. The new decicarbdiox and decitvoc values also fit very well with the dB values for sound, e.g., the optimal odor value of 30 dB corresponds to the ISO Noise Rating Acceptable Value NR 30 for libraries and private offices. They can therefore be compared to each other.

3. It is possible, by comparing dCd and dTv values, to estimate, which component – CO_2 or TVOC – plays a more important role and hence which sources of contamination are more serious.

References

See presented at the end of Part 3 (p. 44).

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