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Measurement of airborne nicotine, as a marker of secondhand smoke exposure, in homes with residents who smoke in 9 European countries

Elisabet Henderson [a], Luis A. Rodriguez Guerrero [a], Xavier Continente [a,b,c], Esteve Fernández [e,f,g,h], Olena Tigova [e,f,g,h], Nuria Cortés-Francisco [a,c], Sean Semple [i], Ruaraidh Dobson [i], Anna Tzortzi [j], Vergina K. Vyzikidou [j], Giuseppe Gorini [k], Gergana Geshanova [l], Ute Mons [m,n], Krzysztof Przewozniak [o,p,q], José Precioso [r], Ramona Brad [s], Maria J. López [a,b,c,d,*], the TackSHS project Investigators[1]

[a] Agència de Salut Pública de Barcelona, Pl. Lesseps, 1, 08023, Barcelona, Spain
[b] Center for Research on Epidemiology and Public Health (CIBERESP), Av. Monforte de Lemos, 3-5, Pabellón 11, Planta 0, 282029, Madrid, Spain
[c] Sant Pau Institute of Biomedical Research (IIB Sant Pau), Sant Antoni Maria Claret, 167, 08025, Barcelona, Spain
[d] Universitat Pompeu Fabra, Departament de Ciències Experimentals i de la Salut (DCEXS), Doctor Aiguader, 88, 08003, Barcelona, Spain
[e] Institut Català d'Oncologia, Av. Granvia de l'Hospitalet 199-203, 08908, L'Hospitalet de Llobregat, Spain
[f] Institut d'Investigació Biomèdica de Bellvitge, Av. Granvia de l'Hospitalet 199, 08908, L'Hospitalet de Llobregat, Spain
[g] Universitat de Barcelona, Feixa Llarga, s/n, 08907, L'Hospitalet de Llobregat, Spain
[h] Center for Biomedical Research in Respiratory Diseases (CIBERES), Av. Monforte de Lemos, 3-5, Pabellón 11, Planta 0, 282029, Madrid, Spain
[i] Institute for Social Marketing and Health, University of Stirling, Stirling, FK9 4LA, Scotland, UK
[j] George D. Behrakis Research Lab, Hellenic Cancer Society, 17B Ipitou str., Athens, 10557, Greece
[k] Istituto per lo Studio, la Prevenzione e la Rete Oncologica (ISPRO), Via Cosimo il Vecchio, 2, 50139, Florence, Italy
[l] Smoke-free Life Coalition, Slivnitsa Blvd, 257, 1202, Sofia, Bulgaria
[m] Faculty of Medicine and University Hospital Cologne, University of Cologne, Kerpener Str. 62, 50923, Cologne, Germany
[n] Cancer Prevention Unit & WHO Collaborating Centre for Tobacco Control, German Cancer Research Center (DKFZ), Im Neuenheimer Feld, 280, 69120, Heidelberg, Germany
[o] Maria Sklodowska-Curie National Research Institute of Oncology, Roentgena, 5, 02-781, Warsaw, Poland
[p] The Foundation Smart Health - Health in 3D, Makolągwy 24, 02-811, Warsaw, Poland
[q] Collegium Civitas, 1 Defilad Square, 00-901, Warsaw, Poland
[r] Research Center in Child Studies, University of Minho, 4710-057, Braga, Portugal
[s] Healthy Romania Generation 2035 Association, Bucharest, Romania

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ABSTRACT

Objective: Smoke-free policies are effective in preventing secondhand smoke (SHS) exposure, but their adoption at home remains largely voluntary. This study aimed to quantify SHS exposure in homes with residents who smoke in Europe according to households' characteristics, tobacco consumption habits, and national contextual factors.

Methods: Cross-sectional study (March 2017–September 2018) based on measurements of air nicotine inside 162 homes with residents who smoke from nine European countries. We installed passive samplers for seven consecutive days to monitor nicotine concentrations. Through self-administered questionnaires, we collected sociodemographic information and the number of individuals who smoke, smoking rules, frequency, location, and quantity of tobacco use in households. Country-level factors included the overall score in the Tobacco Control Scale 2016, the smoking prevalence, and self-reported SHS exposure prevalence. Nicotine concentrations were analyzed as continuous and dichotomous variables, categorized based on the limit of quantification of 0.02 $\mu g/m^3$.

Results: Overall, median nicotine concentration was 0.85 $\mu g/m^3$ (interquartile range (IQR):0.15–4.42), and there was nicotine presence in 93% of homes. Participants reported that smoking was not permitted in approximately 20% of households, 40% had two or more residents who smoked, and in 79% residents had smoked inside during

* Corresponding author. Servei d'Avaluació i Mètodes d'Intervenció (SAMI), Agència de Salut Pública de Barcelona (ASPB), Pl. Lesseps, 1, 08023, Barcelona, Spain.
E-mail address: mjlopez@aspb.cat (M.J. López).
[1] Full list of investigators in the Acknowledgements section.

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the week of sampling. We found higher nicotine concentrations in homes: with smell of tobacco smoke inside (1.45 μg/m^3 IQR: 0.32–6.34), where smoking was allowed (1.60 μg/m^3 IQR: 0.68–7.63), with two or more residents who smoked (2.42 μg/m^3 IQR: 0.58–11.0), with more than 40 cigarettes smoked (2.92 μg/m^3 IQR: 0.97–10.61), and where two or more residents smoked inside (4.02 μg/m^3 IQR: 1.58–11.74). Household nicotine concentrations were significantly higher in countries with higher national smoking prevalence and self-reported SHS exposure prevalence ($p < 0.05$).

Conclusions: SHS concentrations in homes with individuals who smoke were approximately twenty times higher in homes that allowed smoking compared to those reporting smoke-free household rules. Evidence-based interventions promoting smoke-free homes should be implemented in combination with strengthening other MPOWER measures.

1. Introduction

Secondhand smoke (SHS) exposure has been causally linked to numerous adverse health outcomes (U.S. Department of Health and Human Services, 2006) and continues to represent a substantial but preventable burden of disease for children (Carreras et al., 2020) and adults who do not smoke (Carreras et al., 2021) in Europe. The recognition of the harms of SHS led authoritative public health agencies to express the need for promoting and instituting smoke-free environments (CARB, 2005; U.S. Department of Health and Human Services, 2006). As a result, legislation decreeing smoking to be banned in enclosed public spaces has been widely passed, showing clear health benefits (IARC, 2009; Frazer et al., 2016), including reduced hospital admissions for acute coronary syndrome (Pell et al., 2008) reduced asthma-related emergency visits (Croghan et al., 2015), and improved lung function in the general population (Strassmann et al., 2022). In addition, contrary to the hypothesized displacement towards households, smoke-free policies have also incentivized the voluntary introduction of smoking rules in private settings (Mons et al., 2013; Ferketich et al., 2016; Monson and Arsenault, 2017; Tattan-Birch and Jarvis, 2022), where legislative smoking bans could raise concerns from an ethical perspective (Jarvie and Malone, 2008). Home norms on smoking, however, commonly fall short of achieving complete smoke-free environments, as measures tend to be partial (Fu et al., 2019) and can fail to prevent SHS incursions from neighboring residential units (Driezen et al., 2020).

Studies monitoring SHS concentrations with airborne markers (Van Deusen et al., 2009; Martínez-Sánchez et al., 2014a; Semple and Latif, 2014; Semple et al., 2015; Arechavala et al., 2017) and intake with biomarkers (Wipfli et al., 2008; Martínez-Sánchez et al., 2014a; Jain, 2015) suggest SHS exposure within the household environment can be very relevant, especially when smoking is allowed. Households with unrestricted smoking present significantly higher average $PM_{2.5}$ (particulate matter less than 2.5 μm in diameter) (Van Deusen et al., 2009; Semple et al., 2015) and median nicotine levels (Wipfli et al., 2008; Martínez-Sánchez et al., 2014a; Semple et al., 2015) when compared to smoke-free homes. Likewise, biomarker concentrations (i.e. salivary cotinine, urinary cotinine, and nicotine in hair) are directly correlated with domestic environmental nicotine concentrations measured across different contexts (Wipfli et al., 2008; Martínez-Sánchez et al., 2014a; Tattan-Birch and Jarvis, 2022). According to a study based on $PM_{2.5}$ real-time data from over 100 homes with residents who smoke, SHS can linger in the air for up to 5 h after smoking has taken place, representing an invisible but perdurable health risk for individuals who do not smoke (Semple and Latif, 2014). Besides, an added issue to smoking inside dwellings is the exposure to thirdhand smoke (THS), which for prolonged periods accumulates in dust and covers most surfaces of indoor spaces (Matt et al., 2016, 2022).

Earlier research has identified sociodemographic and behavioral factors as predictors of home smoking, smoking rules, and SHS exposure, which, in turn, reflect in tobacco-related health disparities. Lower socioeconomic status (SES) and lower educational attainment have been associated with smoking at home (Pisinger et al., 2012; Kim et al., 2020), higher SHS exposure (Orton et al., 2014; López et al., 2018; Arechavala et al., 2019), and a lower prevalence of household no-smoking rules (Gallus et al., 2016; Fu et al., 2019). Conversely, domestic restrictions on smoking have been more frequently reported by those with greater awareness of the harms of SHS exposure (Abdullah et al., 2014; Orton et al., 2014) and in households with minors (Gallus et al., 2016; Fu et al., 2019) or individuals who do not smoke (Akhtar et al., 2009; Orton et al., 2014; Gallus et al., 2016; Jankowski et al., 2020). Furthermore, a higher number of residents who smoke at home (Akhtar et al., 2009; Arechavala et al., 2017) and not having adopted smoking rules (Akhtar et al., 2009; Arechavala et al., 2017) have been linked to increased SHS exposure level. Moreover, SHS levels at home increase with the number of cigarettes smoked in the living room (Arechavala et al., 2017); and individuals with higher daily cigarette consumption (>30 cigarettes per day) report fewer household no-smoking rules (Fu et al., 2019).

Domestic SHS exposure remains a public health problem entailing great economic cost (Mason et al., 2015; Max et al., 2015). The characterization of SHS exposure in this setting can inform efforts to develop and implement measures aiming at improving public awareness on the health consequences of household SHS exposures and at encouraging the adoption of complete smoke-free homes. However, literature showing objective and comparable data on domestic SHS exposure concentrations at a European level is scarce. Therefore, this study tries to fill this gap by presenting measurements of airborne nicotine in homes with individuals who smoke from nine European countries considering households' characteristics, tobacco consumption, and national contextual factors.

2. Methods

2.1. Study overview

This study is part of the TackSHS project (Fernández et al., 2020), conceived to improve the knowledge on the magnitude and impact of SHS and e-cigarette emissions in Europe. This study represents a cross-sectional analysis on SHS environmental measurements in homes with residents who smoke from nine European countries: Bulgaria, Germany, Greece, Italy, Poland, Portugal, Romania, Spain, and the United Kingdom (UK). Countries were selected to encompass differences in geographical distribution, population size, level of per capita income, national smoking prevalence, and tobacco control policies in Europe. SHS concentrations were measured in a convenience sample of 162 households between March 2017 and September 2018, except for the winter and summer months. Household recruitment was done through snowball sampling. The selection of households was stratified by neighbourhood SES. The neighborhoods' SES was obtained from local synthetic deprivation indexes or other socioeconomic indicators (Henderson et al., 2020). In each country, approximately half the measurements were performed in homes in the most deprived neighborhoods (below the 20th percentile of the country-specific measure of SES distribution) and half in homes in the least deprived neighborhoods (above the 80th percentile of the country-specific measure of SES distribution). Only homes with at least one resident currently smoking daily and with the main participating contact having signed a written informed consent were eligible for the study.

2.2. Nicotine measurements

SHS concentrations in homes were assessed by passively monitoring airborne nicotine, an objective and highly specific marker for SHS (Apelberg et al., 2013). Nicotine passive samplers consisted of a 37-mm diameter plastic cassette containing a filter treated with sodium bisulfate. This procedure for nicotine sampling has been scientifically validated (Hammond et al., 1987) and employed before in residential settings (Arechavala et al., 2017). We placed nicotine samplers for seven consecutive days in the room considered the main area of living of each residential unit. Samplers were hung in a place with air circulation avoiding corners, curtains, or shelves and, where possible, at least 2 m away from the floor and 1 m away from windows or ventilation systems. Researchers involved in the fieldwork received training and were provided with a reference protocol on sampler assembly, coding, collection, and transportation. Nicotine concentrations in filters were determined in the Agència de Salut Pública de Barcelona laboratory through gas chromatography and mass spectrometry. This analytical procedure is accredited by ISO-17025 and had a limit of quantification (LOQ) of 5 ng per filter, which is equal to 0.02 μg/m^3 of nicotine for a week of sampling (10,080 min). We computed time-weighted average nicotine concentrations (in μg/m^3) by dividing the nicotine extracted from the filter by the empirically established airflow rate of 2.4×10^{-5} m^3/min (Hammond et al., 1987) and the time (in minutes) the sampler had been installed. To assess nicotine presence, concentrations were dichotomized based on the LOQ.

2.3. Household tobacco consumption

Smoking habits in the home were ascertained from a self-administered questionnaire completed by the main participating contact at sampler retrieval. The questionnaire was provided in the local language and gathered information about the number of residents who smoked, frequency, location, quantity of smoking at home usually and during the week of nicotine sampling, and information on the household's indoor smoking rules. Respondents were also asked for relevant sociodemographic data such as their educational attainment, and the age and sex of all household members. The highest educational level reported was compared according to each country's compulsory years of schooling. This questionnaire was adapted from a preceding study assessing the validity of self-reported SHS exposure indicators at home (Arechavala et al., 2018).

2.4. Contextual factors

We included national-level tobacco control related covariates in the analyses. Countries were classified into two categories according to their overall score in the Tobacco Control Scale (TCS) 2016 report (Joossens and Raw, 2017). The highest score being 100 points, those below half this score (indicating lower tobacco control efforts) were allocated in a group, and those scoring 50 or above (indicating greater tobacco control efforts) in another, following the evaluation provided by the 2016 report. The TCS tool ranks and compares European countries based on six prioritized measures in a comprehensive tobacco control program: taxation, smoking bans in public places and workplaces, consumer information, bans on advertising and promotion, health warnings on packaging, and cessation aid (Feliu et al., 2020). We also categorized countries considering their national smoking prevalence, overall self-reported SHS exposure prevalence indoors, and self-reported SHS exposure prevalence at home. These data came from a survey on a representative sample of approximately 1000 subjects aged 15 years or more conducted within the TackSHS project in 12 selected European countries during 2017–2018 (Fernández et al., 2020; Gallus et al., 2020). Participants who declared smoking and having smoked at least 100 cigarettes (also roll-your-own cigarettes) throughout their lifetime were defined as individuals who smoke. Non-smokers were individuals who had never smoked and who had formerly smoked. SHS exposure at home occurred when non-smokers reported at least 1 min per day of exposure to SHS at the house. Overall indoor SHS exposure occurred when non-smokers reported at least an average amount of 1 min per day of exposure inside any of the following settings: at home, workplace (the educational venue for students), public (train, tram, bus, subway) and private transportation, and all other indoor places (meaning bars, restaurants, cafeterias, or other leisure places). For all three variables, we used mean values obtained from the entire set of countries involved in the TackSHS survey to create two categories: below or equal to the mean and above the mean (Gallus et al., 2020; Lugo et al., 2022).

2.5. Statistical analyses

We excluded two homes from the analyses, one in Bulgaria and one in Italy, because nicotine concentrations were extremely high (134 μg/m^3 and 445 μg/m^3, respectively) and thus, were considered outliers. Nicotine samples with non-quantifiable levels (n = 11) were assigned half the LOQ value (0.01 μg/m^3) for all analyses (Northrup et al., 2021). Nicotine concentrations were non-normally distributed.

We report descriptive analyses using median and interquartile ranges (IQR) for continuous variables and absolute (n) and relative (%) frequencies for categorical variables. Nicotine concentrations were compared using non-parametric Mann-Whitney U or Kruskal Wallis tests. Differences in categorical variables were assessed by either Chi-squared test or Fisher's exact test, as appropriate. Finally, given that we had 11 samples of nicotine below the LOQ (censored data), we fitted a censored regression model (Tobit model) with log-transformed nicotine concentrations, household tobacco consumption, and contextual factors, adjusting for the respondent's age, sex, and current tobacco use. Predictor variables were theoretically selected to avoid issues with collinearity. For instance, indoor smoking rules were not included in the model because this variable was highly correlated with the places where residents had smoked during the week of sampling. As for the country-level factors, smoking prevalence and overall self-reported SHS exposure prevalence were also related. We opted to keep the smoking prevalence because self-reported SHS exposure might be a less accurate indicator than one's current tobacco use. All analyses were performed with the statistical package Stata v.15.1.

2.6. Ethical considerations

The TackSHS project was approved by the Bellvitge University Hospital Clinical Research Ethics Committee (PR341/15) and this study was approved by local Ethics Committees in each country. The study protocol was registered in ClinicalTrials.gov (ID: NCT03150186). All participants were informed about the aims, methods, and procedures undertaken in the study verbally and through an information sheet; and signed a written informed consent to take part in the study.

3. Results

We analyzed 160 homes with residents who smoke across nine European countries. Characteristics of respondents and households are shown in Table 1. Over half the respondents (60%) were women, the median age was 43.4 years (IQR: 31.3–55.0), 50% had completed university studies, and 66.9% smoked on a daily basis. Most households had three or more members (58.8%) and no minors under 12 years of age (83.8%).

With regard to the smoking habits, 40% of homes had two or more members who smoked and 33.1% had two or more members who usually smoked inside. Participants reported that smoking indoors was not permitted in 21.9% of homes, whereas, in 66.2% it was allowed in specific times or specific areas (partial restrictions) and in 11.9%, smoking was not restricted in any way. During the week of sampling, residents smoked inside the room with the nicotine sampler in 61% of

Table 1
Characteristics of respondents and homes in the study (N = 160). TackSHS project (2017–2018).

Respondent characteristics	Median (IQR)	N
Age (years) (N = 159)	43.4 (31.3–55.0)	159
Sex (N = 159)	**%**	**N**
Male	39.4	63
Female	60.0	96
Educational level (N = 159)		
Primary or lower	1.9	3
Secondary	37.5	60
Tertiary	50.0	80
Studying or other	10.0	16
Tobacco consumption		
Daily	66.9	107
Less than daily	5.0	8
Not at all	28.1	45
Current E-cig use		
Daily	2.5	4
Less than daily	2.5	4
Not at all	95.0	152
Household characteristics		
Households with minors <12 years old		
Yes	16.2	26
No	83.8	134
Number of people living in the house		
1	5.6	9
2	35.6	57
3 or more	58.8	94
Neighbourhood SES[a]		
Most advantaged	47.5	76
Least advantaged	52.5	84
Country		
Bulgaria	11.9	19
Germany	10.6	17
Greece	12.5	20
Italy	11.9	19
Poland	12.5	20
Portugal	11.9	19
Romania	12.5	20
Spain	12.5	20
United Kingdom	3.8	6

Note: IQR, Interquartile Range; SES, socioeconomic status.
[a] Neighbourhood SES: Most advantaged (above the 80th percentile of the neighbourhood SES distribution); Least advantaged (below the 20th percentile of the neighbourhood SES distribution).

homes. For that same period, 70.6% of the respondents detected smell of tobacco smoke inside their residence, and over 40% declared that in total more than 40 cigarettes had been smoked inside the house (Table 2).

Table 3 displays airborne nicotine concentrations in homes considering sociodemographic data and smoking habits. Overall, median nicotine concentration was 0.85 [IQR: 0.15–4.42] μg/m^3 and there was nicotine presence in 93.1% of homes. We found increased median nicotine concentrations and nicotine presence in homes with two or more people who smoked (2.42 μg/m^3 [IQR: 0.58–11.00]; presence: 100%); where two or more people had smoked inside (4.02 μg/m^3 [IQR: 1.58–11.74)]; presence: 100%); with detectable smell of tobacco smoke inside (1.45 μg/m^3 [IQR: 0.32–6.34]; presence: 95.6%); and where, during the week of sampling, more than 40 cigarettes were smoked inside (2.92 μg/m^3 [IQR: 0.97–10.61]; presence: 98.6%); ($p < 0.001$). Moreover, in homes where smoking was totally (1.60 μg/m^3 [IQR: 0.68–7.63]; presence: 100%) or partially allowed (1.69 μg/m^3 [IQR: 0.41–6.42]; presence: 95.3%), median nicotine levels and presence were much higher than in those where smoking was not allowed inside (0.07 μg/m^3 [IQR: 0.03–0.19]; presence: 82.9%). Similarly, median concentrations increased with the proximity to the sampler: 2.06 μg/m^3 [IQR: 0.74–8.43] when smoking occurred in the room the sampler was installed; 0.47 μg/m^3 [IQR: 0.11–1.07] when smoking occurred in another room without the sampler; and 0.06 μg/m^3 [IQR: 0.02–0.15] when smoking occurred outside.

Table 2
Tobacco consumption in homes with smokers in Europe (N = 160). TackSHS project (2017–2018).

	%	N
Number of smokers		
One	60.0	96
Two or more	40.0	64
Number of people smoking inside		
None	20.0	32
One	46.9	75
Two or more	33.1	53
Indoor smoking rules		
Not allowed	21.9	35
Partially allowed	66.2	106
Totally allowed	11.9	19
Places where people smoked the week of sampling (N = 159)		
Nowhere	0.6	1
Only outside[a]	20.1	32
Inside in room without sampler[b]	18.3	29
Inside in room with sampler[c]	61.0	97
Smell of tobacco smoke the week of sampling		
Nowhere	17.5	28
Only outside[a]	11.9	19
Inside	70.6	113
Total cigarettes smoked inside the week of sampling (N = 156)		
0 cigarettes	21.2	33
1–10 cigarettes	10.9	17
11–40 cigarettes	23.7	37
> 40 cigarettes	44.2	69
Hours smoked inside during the last weekday (Median (IQR))	2 (0.5–4)	160
Hours smoked inside during the last weekend day (Median (IQR))	2 (0–6)	160

Note: IQR, Interquartile Range.
[a] On the balcony, terrace, or garden.
[b] Inside in room without sampler: includes smoking reported outside and inside in a room other than the one where the sampler was installed and smoking only inside in a room other than the one where the sampler was installed.
[c] Inside in room with sampler: includes smoking reported outside and inside in rooms with and without the sampler, inside in rooms with and without the sampler, and smoking inside only in the room with the sampler.

Table 4 displays nicotine concentrations in homes according to contextual variables. Median concentrations differed among countries ranging between 0.07 [IQR: 0.03–0.97] μg/m^3 in Germany and 11.10 [IQR: 5.50–18.50] μg/m^3 in Romania. We also found higher nicotine levels in homes located in countries with higher smoking prevalence (1.48 μg/m^3 [0.26–7.63]) ($p < 0.001$), overall self-reported SHS exposure prevalence (2.06 μg/m^3 [0.74–10.61]) ($p < 0.001$), and self-reported SHS exposure prevalence at home (1.68 μg/m^3 [0.36–7.91) ($p < 0.001$). No significant differences were observed with the TCS 2016 overall scores.

As shown in Table 5, except for Germany and Portugal, over 70% of the homes in the other countries partially or totally allowed smoking indoors, and at least one household member usually smoked inside. Moreover, residents had smoked in the room the sampler was installed in the majority of homes from Greece (80.0%), Bulgaria (84.2%), and Romania (100%), meaning smoking in the most trafficked area of the house. Smoking in the room with the sampler was also more frequent in countries with higher national smoking prevalence (72.5% vs. 41.9%, $p < 0.001$), overall higher national self-reported SHS exposure prevalence (84.6% vs. 44.2%, $p < 0.001$), and increased self-reported SHS exposure prevalence at home (70.7% vs. 44.3%, $p < 0.001$). Besides, in such countries, smoking inside the house, partial or no restrictions for smoking inside, and the presence of smell of tobacco smoke were also more prevalent.

Nicotine concentrations were further characterized by bivariate and multivariable regression analyses (Table 6). Nicotine concentrations at homes in Europe significantly increased with the number of individuals who smoked ($\beta = 1.13$ (95% Confidence Interval (CI): 0.57–1.69); when smoking took place indoors: smoking in the room of the sampler ($\beta = 3.40$ (95%CI: 2.72–4.08)), smoking in another room ($\beta = 1.87$ (95%CI:

Table 3
Airborne nicotine concentrations (μg/m^3) according to sociodemographic variables and tobacco consumption in homes with smokers in Europe. TackSHS project (2017–2018).

	N	Median (IQR)	Min	Max	p- value[a]	% presence (n)	p-value[b]
Total	160	0.85 (0.15–4.42)	<LOQ	61.46		93.1 (149)	
Educational level (N = 159)							
Secondary or lower	63	0.59 (0.09–5.10)	<LOQ	61.46	0.568	90.5 (57)	0.480
Tertiary	80	1.01 (0.17–5.57)	<LOQ	55.13		93.8 (75)	
Studying or other	16	0.97 (0.35–1.72)	0.05	13.78		100.0 (16)	
Neighbourhood SES							
Most advantaged	76	0.62 (0.09–4.12)	<LOQ	61.46	0.201	90.8 (69)	0.353
Least advantaged	84	1.03 (0.23–4.42)	<LOQ	55.13		95.2 (80)	
Number of residents who smoke							
One	96	0.35 (0.08–1.68)	<LOQ	55.13	<0.001	88.5 (85)	0.003
Two or more smokers	64	2.42 (0.58–11.00)	0.04	61.46		100.0 (64)	
Number of people smoking inside							
None	32	0.06 (0.02–0.10)	<LOQ	0.57	<0.001	81.3 (26)	0.003
One	75	0.84 (0.26–3.11)	<LOQ	55.13		93.3 (70)	
Two or more	53	4.02 (1.58–11.74)	0.05	61.46		100.0 (53)	
Indoor smoking rules							
Not allowed	35	0.07 (0.03–0.19)	<LOQ	1.06	<0.001	82.9 (29)	0.015
Partially allowed	106	1.69 (0.41–6.42)	<LOQ	61.46		95.3 (101)	
Totally allowed	19	1.60 (0.68–7.63)	0.02	37.40		100.0 (19)	
Places where people smoked the week of sampling (N = 159)							
Nowhere	1	0.03 (-)	–	–	<0.001	100 (1)	0.002
Only outside[c]	32	0.06 (0.02–0.15)	<LOQ	0.57		78.1 (25)	
Inside in room without sampler[d]	29	0.47 (0.11–1.07)	<LOQ	15.7		93.1 (27)	
Inside in room with sampler[e]	97	2.06 (0.74–8.43)	<LOQ	61.46		97.9 (95)	
Smell of tobacco smoke the week of sampling							
Nowhere	28	0.49 (0.12–3.27)	<LOQ	23.44	<0.001	92.9 (26)	0.031
Only outside[c]	19	0.06 (0.03–0.24)	<LOQ	47.65		79.0 (15)	
Inside	113	1.45 (0.32–6.34)	<LOQ	61.46		95.6 (108)	
Total cigarettes smoked inside home the week of sampling (N = 156)							
0 cigarettes	33	0.05 (0.02–0.15)	<LOQ	0.57	<0.001	78.8 (26)	0.004
1 to 10 cigarettes	17	0.22 (0.13–0.56)	<LOQ	13.67		94.1 (16)	
11 to 40 cigarettes	37	0.95 (0.41–2.60)	<LOQ	61.46		94.6 (35)	
> 40 cigarettes	69	2.92 (0.97–10.61)	<LOQ	55.13		98.6 (68)	

Note: IQR, Interquartile Range; LOQ, Limit of quantification (0.02 μg/m^3); SES, socioeconomic status.
[a] Mann-Whitney *U* test or Kruskal-Wallis test.
[b] Chi-squared test or Fisher's exact test.
[c] On the balcony, terrace, or garden.
[d] Inside in room without sampler: includes smoking reported outside and inside in a room other than the one where the sampler was installed and smoking only inside in a room other than the one where the sampler was installed.
[e] Inside in room with sampler: includes smoking reported outside and inside in rooms with and without the sampler, inside in rooms with and without the sampler, and smoking inside only in the room with the sampler.

1.02–2.72)); and in countries with higher national smoking prevalence (β = 0.47 (95%CI: 0.003–0.09)).

4. Discussion

This study across nine European countries reports nicotine concentrations, as a marker of SHS, in households where at least one person who smokes lives. Our results indicated presence of SHS in over nine in ten of the homes analyzed and smoking being allowed indoors in over three-quarters of the homes studied across Europe. In addition to the impact of households' tobacco consumption habits, we found SHS exposure levels also varied substantially by country-level factors such as the national smoking prevalence and the SHS exposure prevalence.

Research built on objective environmental measures offers convincing arguments to substantiate smoking at home as a pending public health problem (Matt et al., 2004, 2016; Van Deusen et al., 2009; Semple et al., 2015; Arechavala et al., 2017). In this study, median SHS concentrations were seven times higher among homes with two or more residents who smoke than among homes with one resident smoking and sixty-seven times higher in homes where two or more residents smoked indoors relative to homes where residents did not smoke inside. These findings are in line with previous literature (Semple et al., 2015; Arechavala et al., 2017) and denote an increased risk from heavy SHS exposure and derived THS exposure (Bahl et al., 2014) for those living with individuals who smoke at home.

Median SHS concentrations were equivalent among homes where smoking was totally and partially allowed and over twenty times the concentrations found among homes where smoking was fully banned. Aligned with these results, Semple et al. (2015) found $PM_{2.5}$ pollution in smoking homes in Scotland to be about ten times higher than in smoke-free homes. Considering nicotine is a more specific marker than fine particulate matter in assessing SHS (Apelberg et al., 2013) the present analyses are more likely to represent the true picture of SHS concentrations in homes where smoking is permitted. Likewise, we found SHS presence in homes where smoking took place indoors but not in the room the sampler was installed, implying SHS spreads throughout the residence. Partial indoor smoking rules are often structured around children and consist of measures like allowing smoking only in designated rooms, on certain occasions, or along with the opening of doors/windows or ventilation systems (Kegler et al., 2016). As reflected in previous studies (Van Deusen et al., 2009; Rees et al., 2014; Arechavala et al., 2017), our results showed limited effectiveness of these strategies to prevent SHS exposures within the household environment. Moreover, the few households in this study reporting total indoor smoking ban adoption and compliance declared smoking occurring outside, on the balcony, terrace, or garden, during the week of sampling. While this strategy likely reduces indoor concentrations, it does not entirely protect others from SHS exposure, as outdoor SHS particles might still infiltrate indoor areas contaminating the air, surfaces, and dust (Matt et al., 2004). Although implementing legal measures in the private realm

Table 4
Airborne nicotine concentrations (μg/m^3) in homes with smokers in Europe according to contextual variables. TackSHS project (2017–2018).

	N	Median (IQR)	Min	p-value[a]		% presence (n)	p-value[b]
Total	160	0.85 (0.15–4.42)	<LOQ	61.46		93.1 (149)	
Country							
Bulgaria	19	2.92 (0.60–11.74)	<LOQ	55.13	<0.001	89.5 (17)	0.022
Germany	17	0.07 (0.03–0.97)	<LOQ	37.40		76.5 (13)	
Greece	20	0.91 (0.43–1.88)	0.10	7.63		100.0 (20)	
Italy	19	0.35 (0.22–1.81)	0.08	15.70		100.0 (19)	
Poland	20	0.64 (0.04–2.39)	<LOQ	22.43		90.0 (18)	
Portugal	19	0.21 (0.04–0.56)	<LOQ	6.39		84.2 (16)	
Romania	20	11.10 (5.50–18.50)	0.97	61.46		100.0 (20)	
Spain	20	0.74 (0.23–4.51)	0.05	13.44		100.0 (20)	
United Kingdom	6	0.78 (0.47–1.61)	0.31	2.06		100.0 (6)	
Tobacco Control Scale score (2016)[c]							
≥ 50 points	104	0.80 (0.19–5.35)	<LOQ	61.46	0.739	95.2 (99)	0.159
< 50 points	56	0.91 (0.10–4.10)	<LOQ	55.13		89.3 (50)	
Smoking prevalence (2017–2018)[d]							
≤ 25.9%	62	0.35 (0.07–1.68)	<LOQ	37.40	<0.001	90.3 (56)	0.265
> 25.9%	98	1.48 (0.26–7.63)	<LOQ	61.46		94.9 (93)	
SHS exposure prevalence (2017–2018)[e]							
≤ 30.9%	95	0.32 (0.07–1.81)	<LOQ	37.40	<0.001	90.5 (86)	0.202
> 30.9%	65	2.06 (0.74–10.61)	<LOQ	61.46		96.9 (63)	
SHS exposure prevalence in homes (2017–2018)[f]							
≤ 13.1%	61	0.31 (0.07–1.06)	<LOQ	37.40	<0.001	88.5 (54)	0.106
> 13.1%	99	1.68 (0.36–7.91)	<LOQ	61.46		96.0 (95)	

Note: IQR, Interquartile Range; LOQ, Limit of quantification (0.02 μg/m^3).
[a] Mann-Whitney *U* test or Kruskal-Wallis test.
[b] Chi-squared test or Fisher's exact test.
[c] Tobacco Control Scale (2016) overall score: ≥50 (Italy, Poland, Portugal, Romania, Spain, United Kingdom); <50 (Bulgaria, Germany, Greece).
[d] Based on a European survey conducted in the TackSHS project. Smoking prevalence (overall mean): ≤25.8 (Germany, Italy, Poland, United Kingdom); >25.8 (Bulgaria, Greece, Portugal, Romania, Spain).
[e] Based on a European survey conducted in the TackSHS project. SHS exposure prevalence (overall mean): ≤31.2 (Germany, Italy, Poland, Portugal, Spain); >31.2 (Bulgaria, Greece, Romania, United Kingdom).
[f] Based on a European survey conducted in the TackSHS project. SHS exposure prevalence in homes (overall mean): ≤13.3 (Germany, Italy, Portugal, United Kingdom); >13.3 (Bulgaria, Greece, Poland, Romania, Spain).

might be controversial, our results call for urgent tobacco control initiatives that stimulate non-smoking bans in households with residents who smoke, perhaps by stressing the multiple benefits of smoke-free homes (IARC, 2009; Mills et al., 2009; Semple et al., 2022).

Homes of respondents declaring smell of tobacco smoke in the indoor areas had significantly higher SHS concentrations and presence than homes where the smell of tobacco smoke was perceived "nowhere" and "only outside". Cigarette smoke odor is a warning of SHS exposure, but it might also signal the incursion of SHS from neighboring residences (Snyder et al., 2016; Wilson et al., 2017). Given the well-known health risks of smoking and SHS exposures at home (U.S. Department of Health and Human Services, 2006), some jurisdictions in the United States (U.S.) have taken action in this matter. At the local level, the city of Belmont, California, as of 2009, outlawed tobacco consumption in multi-unit residence common areas and inside any apartment sharing at least one floor or ceiling with another unit (Belmont City Council, 2007). In 2017, the City of New York passed a law that mandates residential buildings of three or more units to establish a smoking policy to be disclosed to present and future tenants (The New York City Council, 2017). Also, since July 2018, a nationwide ban, enacted by the U.S. Department of Housing and Urban Development, forbids smoking in public housing units, its common areas, and within 25 feet of public housing grounds (U.S. Department of Housing and Urban Development, 2016). Yet, to date, European countries lack this sort of legislative measures aiming for smoke-free homes.

We did not observe significant differences in the SHS exposure by neighbourhood SES or the respondent's educational attainment. Earlier literature drawing from homes at the population level, including smoking and non-smoking households, has reported a strong relationship between lower SES and household SHS exposures (Bonevski et al., 2014; Abdullah et al., 2014; López et al., 2018; Gallus et al., 2016). Our analyses, however, targeted one particular group of homes (those with at least one resident who smokes) where certain behaviors towards cigarette smoking and no-smoking rules might not be that different. Besides, this study counts with a limited number of conveniently selected homes, where we might have inadvertently had an over-representation of households that allowed smoking inside (almost 80% of the homes in this study permitted smoking). In addition, considerations about the health risks for children of inhaling SHS or the future consequences of normalizing tobacco use are amongst the most commonly cited arguments to implement voluntarily smoke-free homes (Phillips et al., 2007). Nevertheless, in the present analyses, eight out of ten households did not have minors below the age of twelve, and in four out of ten, more than two members were smokers.

There were geographical disparities in SHS exposure at homes across Europe. While the country differences should not be over-interpreted given the nature of our sample, we found greater SHS concentrations but not SHS presence in homes from countries with higher national smoking prevalence. This result might be partly confounded by the association between homes in countries with higher national smoking prevalence and smoking in the room the sampler was placed. However, a positive association was also observed with smoking prevalence in the multivariable analyses. Our findings are consistent with prior research assessing SHS exposure at other indoor and outdoor areas in Europe (Filippidis et al., 2016; Henderson et al., 2020, 2021), suggesting SHS exposure and smoking prevalence are closely related factors. Equally, SHS concentrations were more prominent among households in countries with greater self-reported indoor SHS exposure prevalence, overall and at home. For both these variables, homes from countries with higher self-reported SHS exposure prevalence also showed a higher prevalence of people smoking inside, allowing smoking indoors, smell of tobacco smoke inside, and smoking in the room with the sampler. In this sense, our findings link more intense SHS exposures to contextual factors, meaning SHS exposure at home is also influenced by national-level

Table 5
Smoking-related data in homes with smokers in Europe according to contextual variables. TackSHS project (2017–2018).

	N	People smoking inside home % (n)	Partially or totally allowed smoking inside home %(n)	Smell of tobacco smoke inside home %(n)	Smoked inside the room with sampler[a]% (n)
Total	160	80.0 (128)	78.1 (125)	70.6 (113)	60.6 (97)
Country					
Bulgaria	19	94.7 (18)	100.0 (19)	84.2 (16)	84.2 (16)
Germany	17	35.3 (6)	41.2 (7)	76.5 (13)	23.5 (4)
Greece	2	90.0 (18)	90.0 (18)	75.0 (15)	80.0 (16)
Italy	19	100.0 (19)	73.7 (14)	57.9 (11)	63.2 (12)
Poland	20	80.0 (16)	85.0 (17)	70.0 (14)	35.0 (7)
Portugal	19	47.4 (9)	47.4 (9)	42.1 (8)	42.1 (8)
Romania	20	100.0 (20)	100.0 (20)	80.0 (16)	100.0 (20)
Spain	20	80.0 (16)	75.0 (15)	70.0 (14)	55.0 (11)
United Kingdom	6	100.0 (6)	100.0 (6)	100.0 (6)	50.0 (3)
p-value[b]		<0.001	<0.001	0.002	<0.001
Tobacco Control Scale score (2016)[c]					
≥ 50 points	104	82.7 (86)	77.9 (81)	66.4 (69)	58.7 (61)
< 50 points	56	75.0 (42)	78.6 (44)	78.6 (44)	64.3 (36)
p-value[2]		0.246	0.920	0.139	0.403
Smoking prevalence (2017–2018)[d]					
≤ 25.9%	62	75.8 (47)	71.0 (44)	71.0 (44)	41.9 (26)
> 25.9%	98	82.7 (81)	82.7 (81)	70.4 (69)	72.5 (71)
p-value[2]		0.292	0.082	0.380	<0.001
SHS exposure prevalence (2017–2018)[e]					
≤ 30.9%	95	69.5 (66)	65.2 (62)	63.2 (60)	44.2 (42)
> 30.9%	65	95.4 (62)	96.9 (63)	81.5 (53)	84.6 (55)
p-value[2]		<0.001	<0.001	0.001	<0.001
SHS exposure prevalence in homes (2017–2018)[f]					
≤ 13.1%	61	65.6 (40)	59.0 (36)	62.3 (38)	44.3 (27)
> 13.1%	99	88.9 (88)	89.9 (89)	75.8 (75)	70.7 (70)
p-value[2]		<0.001	<0.001	0.015	<0.001

[a] Inside in room with sampler: includes smoking reported outside and inside in rooms with and without the sampler, inside in rooms with and without the sampler, and smoking inside only in the room with the sampler.
[b] Chi-squared test or Fisher's exact test.
[c] Tobacco Control Scale (2016) overall score: ≥50 (Italy, Poland, Portugal, Romania, Spain, United Kingdom); <50 (Bulgaria, Germany, Greece).
[d] Based on a European survey conducted in the TackSHS project. Smoking prevalence (overall mean): ≤25.8 (Germany, Italy, Poland, United Kingdom); >25.8 (Bulgaria, Greece, Portugal, Romania, Spain).
[e] Based on a European survey conducted in the TackSHS project. SHS exposure prevalence (overall mean): ≤31.2 (Germany, Italy, Poland, Portugal, Spain); >31.2 (Bulgaria, Greece, Romania, United Kingdom).
[f] Based on a European survey conducted in the TackSHS project. SHS exposure prevalence in homes (overall mean): ≤13.3 (Germany, Italy, Portugal, United Kingdom); >13.3 (Bulgaria, Greece, Poland, Romania, Spain).

Table 6
Multivariable analyses (Tobit models) of log-transformed nicotine concentrations in homes with smokers in Europe. TackSHS project (2017–2018).

	Bivariate model	Multivariable model	
	β (95% CI)	β (95% CI)	Pseudo R^2
Constant		−5.71 (−7.90, −3.51)	0.1743
Number of smokers (ref. one)	1.98 (1.28, 2.68)	1.13 (0.57, 1.69)	
Places where people smoked[a] (ref. outside)			
Inside without sampler	2.18 (1.28, 3.08)	1.87 (1.02, 2.72)	
Inside with sampler	3.96 (3.25, 4.67)	3.40 (2.72, 4.08)	
National smoking prevalence[b] (continuous)	0.07 (0.01, 0.13)	0.047 (0.003, 0.09)	

Note: CI, Confidence Interval; ref, reference.
Adjusted for the respondent's sex, age, and tobacco use.
[a] Inside in room with sampler: includes smoking reported outside and inside in rooms with and without the sampler, inside in rooms with and without the sampler, and smoking inside only in the room with the sampler.
[b] Based on a European survey conducted in the TackSHS project.

characteristics. Therefore, strengthening additional demand reduction measures, namely taxation on tobacco products and tobacco cessation treatment (Gravely et al., 2017; Feliu et al., 2019; Flor et al., 2021), seems critical to decreasing SHS exposures, especially in private settings in Europe, where smoking restrictions are mainly voluntary.

A few ecological studies have assessed the relationship between tobacco control policies and the degree of smoking permissiveness in homes across Europe. Ferketich et al. (2016) reported a positive correlation between the TCS scores and the prevalence of in-home non-smoking rules, whereas Martínez-Sánchez et al. (2014b) did not find any association. In the present study, we did not observe significant differences in the adoption of smoking rules or SHS exposure levels according to the 2016 overall TCS scores. Our results might be explained by the categorization of the sites from Romania, with 56 points, in the higher TCS scores group. When compared to the other countries, Romanian households had substantially higher median nicotine concentrations and tobacco consumption habits.

There were some limitations to this study. First, these analyses included only homes with individuals who smoke selected based on convenience sampling. Although this constrains the external validity of

our results and, hence, our ability to generalize over households from the same region, it does not undermine our primary objective: assess SHS concentrations in homes with individuals who smoke according to several exposure determinants. Secondly, we used a self-administered questionnaire, which is prone to recall and social desirability biases, to gather sociodemographic data, smoking rules, and tobacco consumption habits. The questionnaire, however, addressed day-to-day tobacco-related behaviors, which had a maximum recall period of a week, in households that volunteered to participate in the study. Even though households were voluntarily recruited, the presence of nicotine samplers might have also altered smoking behaviors within the home, but we would expect this limitation to rather introduce a conservative bias, with the concentrations reported underestimating actual SHS exposures at homes with residents who smoke. Finally, we were unable to assess the influence of other home characteristics, such as the type of dwelling, and the SHS incursions from neighboring units because we did not include this information in the questionnaire. Still, SHS infiltrations would have probably had a higher impact on the SHS exposure levels if analyzing homes from people who do not smoke.

To the best of our knowledge, this is of the largest studies providing objective data on SHS exposure in households with residents who smoke in Europe. Following a previously employed (Arechavala et al., 2017) and validated methodology (Hammond et al., 1987), we measured vapor-phase nicotine concentrations in a type of household that might be more reluctant to become smoke-free. Unlike $PM_{2.5}$, released while smoking but also by other sources of combustion like some household appliances (furnaces, heaters, and stoves), airborne nicotine is unique to tobacco smoke, and thus, a specific marker to SHS (Hammond et al., 1987; Apelberg et al., 2013). The fact we have analyzed nicotine concentrations according to country-level factors also constitutes one of the strengths of this study since, to the best of our knowledge, there are no previous analyses in homes that account for such contextual factors.

5. Conclusions

Despite the strong health rationale to ban tobacco use in indoor settings and the progress shown in some European countries by doing so in privately-owned vehicles (Laverty and Been, 2021), many still might argue households are not within the public authority's sphere of competence. This study evidenced SHS can reach very high concentrations in smoking homes where residents who do not smoke, such as children and the elderly, might routinely experience SHS and THS exposures. Taken together, our results highlight the need for evidence-based interventions aiming at eliminating SHS from homes in Europe. However, based on the influence of country-level factors, the focus should not be put only on encouraging the adoption of complete smoke-free households refraining those who smoke from smoking, but also on reducing national smoking rates by intensifying efforts on other MPOWER measures.

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Disclaimer

This paper reflects only the authors' views and the European Commission is not responsible for any use that may be made of the information it contains.

Credit

Elisabet Henderson: Formal analysis, Writing – Original Draft, Visualization. **Luis A Rodriguez Guerrero**: Methodology, Visualization, Writing – Review & Editing. **Xavier Continente**: Conceptualization, Investigation, Validation, Writing – Review & Editing. **Esteve Fernández**: Funding acquisition, Investigation, Writing – Review & Editing. **Olena Tigova**: Investigation, Writing – Review & Editing. **Nuria Cortés-Francisco**: Investigation, Writing – Review & Editing. **Sean Semple**: Investigation, Writing – Review & Editing. **Ruaraidh Dobson**: Investigation, Writing – Review & Editing. **Anna Tzortzi**: Investigation, Writing – Review & Editing. **Vergina K Vyzikidou**: Investigation, Writing – Review & Editing. **Giuseppe Gorini**: Investigation, Writing – Review & Editing. **Gergana Geshanova**: Investigation, Writing – Review & Editing. **Ute Mons**: Investigation, Writing – Review & Editing. **Krzysztof Przewozniak**: Investigation, Writing – Review & Editing. **José Precioso**: Investigation, Writing – Review & Editing. **Ramona Brad**: Investigation, Writing – Review & Editing. **Maria J. López**: Conceptualization, Writing – Review & Editing, Project Administration, Funding acquisition.

Ethical considerations

The TackSHS project was approved by the Bellvitge University Hospital Clinical Research Ethics Committee (PR341/15) and this study was approved by local Ethics Committees in each country (See table below for Ethic Committee name and code). The study protocol was registered in ClinicalTrials.gov (ID: NCT03150186). All participants were informed about the aims, methods, and procedures undertaken in the study verbally and through an information sheet; and signed a written informed consent to take part in the study.

Country	Name of Ethic Committee	Code EC
TackSHS Project	Bellvitge University Hospital Clinical Research Ethics Committee	PR341/15
Bulgaria	Ethics Committee of the Bulgarian Academy of Sciences	269/September 30, 2016
France	Comite de protection des personnes sud-est I	2017-A02959-44
Germany	Ethikkommission der medizinischen fakultät heidelberg	S-663/2016
Greece	National and Kapodistrian University of Athens	1,617,006,410
Ireland	Institiúid Teicneolaíochta Átha Cliath - Dublin Institute of Technology	16–127
Italy	Comitato Etico Regionale per la Sperimentazione Clinica della Regione Toscana (Area Vasta Centro)	11,013_oss
Poland	Państwowa Uczelnia Zawodowa w Ciechanowie - Wydzialu Ochrony Zdrowia i Nauk Humanistycznych	February 2016
Portugal	SECVS Universidade do Minho	SECVS 050/2016
Romania	Academia De Ştiinţe Medicale - Comisia de Bioetica a Medicamentului si a Dispozitivelor Medicale	30 SNI
Spain	Parc de Salut MAR – Clinical Research Ethics Committee	2016/6725/I
United Kingdom	Ethical Review Board of the College of Life Sciences and Medicine of the University of Aberdeen	CERB/2017/3/1421

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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[1]The TackSHS Project Investigators:

Catalan Institute of Oncology (ICO); Bellvitge Biomedical Research Institute (IDIBELL), Spain: Esteve Fernández, Yolanda Castellano, Marcela Fu, Montse Ballbè, Beladenta Amalia, Olena Tigova.

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Istituto per lo Studio, la Prevenzione, e la Rete Oncologica (ISPRO), Italy: Giuseppe Gorini, Giulia Carreras, Barbara Cortini, Simona Verdi, Alessio Lachi, Elisabetta Chellini.

Polytechnic University of Cartagena (UPCT), Spain: Ángel López Nicolás, Marta Trapero-Bertran, Daniel Celdrán Guerrero.

European Network on Smoking and Tobacco Prevention (ENSP), Belgium: Cornel Radu-Loghin, Dominick Nguyen, Polina Starchenko.

Hospital Universitario La Princesa (IISP), Spain: Joan B Soriano, Julio Ancochea, Tamara Alonso, María Teresa Pastor, Marta Erro, Ana Roca, Patricia Pérez, Elena García Castillo.

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