The joint association of air pollution and noise from road traffic with cardiovascular mortality in a cohort study

R Beelen, G Hoek, D Houthuijs, P A van den Brandt, R A Goldbohm, P Fischer, L J Schouten, B Armstrong and B Brunekreef

Occup. Environ. Med. 2009;66;243-250; originally published online 18 Nov 2008; doi:10.1136/oem.2008.042358

The joint association of air pollution and noise from road traffic with cardiovascular mortality in a cohort study

R Beelen,[1] G Hoek,[1] D Houthuijs,[2] P A van den Brandt,[3] R A Goldbohm,[4] P Fischer,[2] L J Schouten,[3] B Armstrong,[5] B Brunekreef[1,6]

[1] Institute for Risk Assessment Sciences, Division of Environmental Epidemiology, Utrecht University, Utrecht, The Netherlands; [2] Centre for Environmental Health Research, National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands; [3] Department of Epidemiology, Maastricht University, Maastricht, The Netherlands; [4] TNO Quality of Life, Department of Food and Chemical Risk Analysis, Zeist, The Netherlands; [5] Public and Environmental Research Unit, London School of Hygiene and Tropical Medicine, London, UK; [6] Julius Center for Health Sciences and Primary Care, University Medical Center Utrecht, Utrecht, The Netherlands

Correspondence to: Bert Brunekreef, Institute for Risk Assessment Sciences, Division of Environmental Epidemiology, Utrecht University, PO Box 80178, 3508 TD Utrecht, The Netherlands; b.brunekreef@uu.nl

Accepted 19 September 2008
Published Online First 18 November 2008

ABSTRACT

Objectives: Associations between cardiovascular mortality and air pollution and noise together were investigated.

Methods: Data from the ongoing Netherlands Cohort Study on Diet and Cancer (120 852 subjects; follow-up 1987–1996) were used. Cox proportional hazard analyses were conducted for the association between cardiovascular mortality and exposure to black smoke, traffic intensity on the nearest road and road traffic noise at the home address.

Results: The correlations between traffic noise and background black smoke, and traffic intensity on the nearest road were moderate at 0.24 and 0.30, respectively. Traffic intensity was associated with cardiovascular mortality, with highest relative risk (95% confidence interval) for ischaemic heart disease (IHD) mortality being 1.11 (1.03 to 1.20) (increment 10 000 motor vehicles/24 h). Relative risks for black smoke concentrations were elevated for cerebrovascular (1.39 (0.99 to 1.94)) and heart failure mortality (1.75 (1.00 to 3.05)) (increment 10 $\mu g/m^3$). These associations were insensitive to adjustment for traffic noise. There was an excess of cardiovascular mortality in the highest noise category (>65 dB(A)), with elevated risks for IHD (1.15 (0.86 to 1.53)) and heart failure mortality (1.99 (1.05 to 3.79)). After adjustment for black smoke and traffic intensity, noise risk reduced to unity for IHD mortality and was slightly reduced for heart failure mortality.

Conclusions: Associations between black smoke concentrations and traffic intensity on the nearest road with specific cardiovascular causes of death were not explained by traffic noise in this study.

Cohort studies have shown associations between long-term exposure to particulate matter air pollution and cardiovascular mortality.[1–4] Cohort studies which were mostly conducted in Europe have reported associations between traffic-related air pollution and cardiovascular mortality.[5–7] Exposure to traffic-related air pollution has been assessed using dispersion modelling,[7] measured or modelled air pollution data and traffic variables assessed with geographical information systems.[5 6 8 9]

Motorised traffic is an important source not only of air pollution but also of noise.[10 11] Exposure to traffic noise is associated with ischaemic heart disease (IHD)[10] and is usually modelled using traffic intensity, traffic composition, speed, distance to roads, noise barriers and other factors as input variables.

The joint association of long-term exposure to air pollution and noise with cardiovascular mortality has not been described before, although we previously reported an association between traffic-related air pollution, traffic intensity and mortality in a Dutch cohort.[12] In this paper, we study the joint association of long-term exposure to air pollution, traffic intensity and noise with cardiovascular mortality. Because air pollution and noise may be associated with different cardiovascular endpoints,[7 9–11 13 14] we studied overall cardiovascular mortality as well as subcategories of cardiovascular mortality.

METHODS

Study design

The cohort has been described in detail previously.[15] Briefly, the Netherlands Cohort Study on Diet and Cancer (NLCS) started in September 1986 with 120 852 subjects aged 55–69 years living in 204 municipalities located throughout the country. The NLCS study was designed as a case-cohort study, that is, cases are derived from the entire cohort, while the person-years at risk are estimated from a random subcohort (n = 5000).[16] However, in our analyses we will use data from all participants.

At baseline, all participants completed an 11-page questionnaire on risk factors for cancer. For all participants, data from one machine readable page of the questionnaire were entered (with information about age, gender and smoking status). The exact residential address at baseline was also available. The entire cohort was followed up for cancer incidence and mortality.[17] For emerging cases and the randomly selected subcohort, the remaining 10 questionnaire pages (not machine readable) were manually entered. As a result, only limited confounder information is available for the full cohort.

Mortality data for the period 1987–1996 were obtained from the Dutch Central Bureau of Genealogy and Statistics Netherlands. Completeness of case ascertainment could be checked by using information from the subcohort (n = 5000), which has been followed biennially. The completeness of mortality follow-up was estimated to be over 99%. Cause of death information from death certificates which were filled in by a physician was available from Statistics Netherlands. A cause of death was available for 99.7% of cases and was coded according to the International Classification of Diseases, ninth

revision (ICD-9) for the period 1986–1995 and ICD-10 for 1996. In our analyses we used the primary cause of death. Cardiovascular mortality was grouped into IHD, cerebrovascular, heart failure and cardiac dysrhythmia mortality (table 1).

The NLCS study was approved by institutional review boards from Maastricht University and the Netherlands Organization for Applied Scientific Research (TNO). All cohort members consented to participation by completing the mailed, self-administered questionnaire.

Air pollution

The air pollution exposure assessment method has been described previously.[18] Long-term exposure to outdoor air pollution was estimated at the 1986 home addresses, which were geocoded into standard Dutch geographic coordinates (Address Coordinates Netherlands (ACN)) using a database with high geographical accuracy from 2000.[12]

Exposure was estimated as the sum of regional, urban and local traffic contributions. Regional background concentrations were estimated using interpolation of data from regional background sites in the national monitoring network. The interpolation method was validated using cross-validation.[18] The urban component was estimated using regression models relating measured urban concentrations to the number of inhabitants around a monitoring site. The sum of the regional and urban contributions was defined as background concentration. Average background concentrations for the period 1987–1996 were estimated for black smoke, nitrogen dioxide (NO_2), and fine particles less than 2.5 μm in diameter ($PM_{2.5}$). Average background concentrations were assigned to the 1986 home address. In this paper we used black smoke concentrations as it is a measure of the traffic-related component of particles.

Local traffic contributions were characterised by traffic variables which were assessed using a geographical information system (GIS) and a digital road network (from the year 2001) with linked traffic intensities for 1986.[18] A background traffic intensity value of 1225 motor vehicles (mvh)/24 h was assigned to roads without traffic intensities, assuming that these are not major roads. This was done to avoid underestimation of local traffic contributions, for example when calculating traffic intensity in a buffer. A value of 1225 mvh/24 h was used because this was half of the value of 2450 mvh/24 h that was used in the Dutch Environmental Traffic Maps to distinguish between roads for which air pollution assessments were and were not made. Approximately 80% of the participants had an assigned traffic intensity on the nearest road of 1225 mvh/24 h.[18] Assessed traffic variables were the traffic intensity on the nearest road, the sum of traffic intensity in a 100 m buffer around a residential address, and an indicator variable for living near a major road (ie, living within 100 m of a motorway and/or within 50 m of a local road with traffic intensity >10 000 mvh/24 h). In this paper we used traffic intensity on the nearest road as an indicator for local traffic contributions because it had the strongest association with cardiovascular mortality.[12] In addition, studies have shown that there are important variations in the concentrations close to busy roads.[18] Other studies have also used traffic variables as an indicator for proximity to busy roads.[5 6 8 9] Because addresses were geocoded with a database from 2000 and the digital road network was from 2001, coordinates and the road network are compatible.

Urban background black smoke concentration and traffic intensity were separately analysed to identify separate effects of living near a busy road.

Table 1 Number of deaths during follow-up*

Cause	ICD-9 codes	ICD-10 codes	Number of deaths
Cardiovascular mortality	400–440	I10–I70	6137
Ischaemic heart disease mortality	410–414	I20–I25	3521
Cerebrovascular mortality	430–438	I60–I69	1175
Heart failure mortality	428	I50	422
Cardiac dysrhythmia mortality	427	I44–I49	339

*ICD, International Classification of Diseases.

Traffic noise

Road traffic noise at the 1986 home address was estimated for all subjects using EMPARA, a state-of-the-art model for noise mapping in the Netherlands (resolution 25×25 m). Traffic noise was modelled as equivalent A-weighted yearly average sound pressure levels (dB(A)).[19] The model is based upon standard noise calculation methods used in the Netherlands.[20] Input variables for the model are traffic intensity, traffic composition and traffic speed (determining noise emission), distance to roads, land use (hard versus soft surface; density of built-up area), location of noise barriers and quiet asphalt (determining transmission).[19] Input data were collected for the period 2000–2001 because not all required data for 1986 were available. Traffic intensities are a major input variable in these models. We documented that while absolute traffic intensities increased during the follow-up period (1987–1996), traffic intensity data for 1986 and 1996 were highly correlated (>0.9).[18] Other important factors such as distance to roads and density of the built-up area were likely stable as well.

The validity of EMPARA has been evaluated for both rural and urban locations using measured data and calculations with more detailed noise models. Both the measured and calculated values differed on average less than 2–3 dB(A) from the EMPARA results.[19] The range in modelled noise levels was 29–75 dB(A).

As noise exposure indicator, we used the standard measure for noise exposure in the Netherlands before the implementation of the European Noise Directive.[21] This was defined as the maximum of the annual average noise level during the day (07:00–19:00 h), the evening (19:00–23:00 h) or the night (23:00–07:00 h). Levels during the evening and night receive a penalty of 5 and 10 dB(A), respectively.[19] No information was available for other noise indicators such as background noise or the number of noise events.

Statistical analysis

We conducted analyses in the full cohort using Cox proportional hazards models. Person-years were calculated for all participants from baseline until death or end of follow-up. Person-years for subjects who died from causes other than those being analysed were defined censored at the time of death in cause-specific analyses.

We added urban background black smoke concentration and traffic intensity on the nearest road as continuous variables to assess the potential confounding effects of adding traffic noise especially to the traffic intensity variables.

Effects of traffic noise exposure were analysed with noise classified into categories of 5 dB(A), from ⩽50 dB(A) to >65 dB(A). These categories were chosen to address thresholds which have been observed in previous studies.[10]

Effects of air pollution and noise were investigated separately and together. Relative risks (RR) were calculated for black

smoke concentration and traffic intensity differences between the 5th and the 95th percentile: this was rounded to 10 μg/m^3 and 10 000 motor vehicles/24 h, respectively. Relative risks for noise were calculated with ⩽50 dB(A) as reference category.

We adjusted for gender, age at baseline and smoking status coded as never, ex and current smoking separately for cigarette, cigar and pipe smoking. We further adjusted for indicators of socio-economic status of the neighbourhood (average size 3.6 km^2) and COROP scale (40 areas; average size ~1000 km^2) as in our previous paper (table 2).[12]

Because we conducted analyses in the full cohort, only a limited number of confounders was available. Comparing this limited set of confounders with the full confounder set in case-cohort analyses indicated that this limited set of confounders was sufficient to adjust for confounding in the air pollution analyses in this cohort.[12]

We did not adjust for spatial clustering as it was previously not found to be important.[12]

Data management was carried out using SPSS 12.0 (SPSS, Chicago, IL) and statistical analyses were conducted using Stata statistical software 8 (Stata, College Station, TX). GIS calculations were conducted using ArcInfo (ESRI, Redlands, CA).

Additional analyses

As a sensitivity analysis, we investigated traffic intensity on the nearest road as a categorical variable (⩽1225 mvh/24 h (reference category), 1225–10 000 mvh/24 h and >10 000 mvh/24 h).

Further, we conducted analyses with NO_2 and $PM_{2.5}$ background concentrations and with other traffic variables (living near a major road and traffic intensity in a 100 m buffer).

We investigated traffic noise as continuous variable in a linear model.

Table 2 Descriptive characteristics of cardiovascular mortality cases and non-cases according to various baseline characteristics (among subjects for whom geographical coordinates of the home address were available (n = 117 528))

Characteristic	Cases (n = 6137)	Non-cases in full cohort (n = 111 391)
Gender (men)	4243 (69.1%)	52 558 (47.2%)
Age (years)	64 (61–67)	62 (58–65)
Cigarette smoking status		
Never	1620 (28.6%)	43 281 (41.3%)
Ex	1859 (32.8%)	33 103 (31.6%)
Current	2182 (38.5%)	28 350 (27.1%)
Cigar smoking status		
Never	4822 (82.4%)	93 776 (87.8%)
Ex	552 (9.4%)	7271 (6.8%)
Current	475 (8.1%)	5807 (5.4%)
Pipe smoking status		
Never	5381 (91.3%)	100 197 (93.4%)
Ex	318 (5.4%)	4747 (4.4%)
Current	194 (3.3%)	2305 (2.2%)
Percentage of persons with low income in neighbourhood	41 (36–47)	41 (36–46)
Percentage of persons with high income in neighbourhood	18 (12–24)	19 (13–25)
Percentage of persons with low income in a COROP area*	41 (36–45)	41 (36–45)
Percentage of persons with high income in a COROP area*	19 (18–23)	19 (18–23)

*COROP areas consist of a central point (eg, a city) and the surrounding economic and social region. The Netherlands is divided in 40 COROP areas.
Values are number (percentage) or median (interquartile range).

Sensitivity analyses with exclusion of observations with traffic noise above 65 dB(A) were conducted. We also conducted sensitivity analyses with exclusion of subjects for whom no traffic data were available.

We conducted separate analyses for men and women because most previous studies investigated the noise effects in men only.[10] We investigated effect modification by age (age <62 years and age >62 years), cigarette smoking status (never/ex/current) and percentage of persons with low income in the neighbourhood (in tertiles). Heterogeneity in relative risk estimates between different subgroups was tested using Cochran's Q test.[22]

RESULTS

For 97% of the subjects we were able to estimate air pollution and noise at the home address (n = 117 528). About 57% of all cardiovascular deaths were caused by IHD (table 1). Cardiovascular mortality cases were older and more likely to be male or current smokers compared to non-cases (table 2).

Air pollution and traffic noise

Background black smoke, traffic intensity on the nearest road and noise varied substantially within the cohort (fig 1). Overall, 7.5% of the subjects were exposed to traffic noise of between 60 and 65 dB(A), and 1.6% to traffic noise above 65 dB(A). For 4.5% of the subjects, traffic intensity on the nearest road was >10 000 mvh/24 h.

Traffic noise exposure was higher for subjects who had a traffic intensity >10 000 mvh/24 h on the nearest road (mean 60 dB(A)) compared to subjects who had a traffic intensity ⩽10 000 mvh/24 h on the nearest road (mean 52 dB(A)).

The correlations between traffic noise and background black smoke, and traffic intensity on the nearest road were moderate at 0.24 and 0.30, respectively. The correlation between traffic noise and traffic intensity for subjects with noise levels above 65 dB(A) was slightly lower at 0.22.

Association of air pollution and traffic noise with cardiovascular mortality

Table 3 shows the associations between background black smoke, traffic intensity on the nearest road and traffic noise with cardiovascular mortality. Traffic intensity on the nearest road was associated with cardiovascular mortality, with the highest relative risk being for IHD mortality. Relative risks for background black smoke concentrations were elevated for cerebrovascular and heart failure mortality. The associations for background black smoke concentrations and traffic intensity were insensitive to adjustment for traffic noise.

There was an excess of cardiovascular mortality in the highest noise category (>65 dB(A)), which was concentrated especially in heart failure mortality (RR 1.99 (95% confidence interval (CI) 1.05 to 3.79). This relative risk was based on only 10 cases, which is reflected in the wide confidence intervals. The numbers of cases in the highest noise category for the other mortality outcomes were: 94 for cardiovascular mortality, 49 for IHD mortality, 14 for stroke mortality, 10 for heart failure mortality and 6 for cardiac dysrhythmia mortality.

After adjustment for black smoke concentrations and traffic intensity, the association for IHD mortality reduced to unity and the association for heart failure mortality was slightly reduced to 1.90.

Crude estimates (only age and gender adjusted) only slightly differed from the adjusted estimates with relative risks for cardiovascular mortality of 1.15 (95% CI 1.03 to 1.29) for

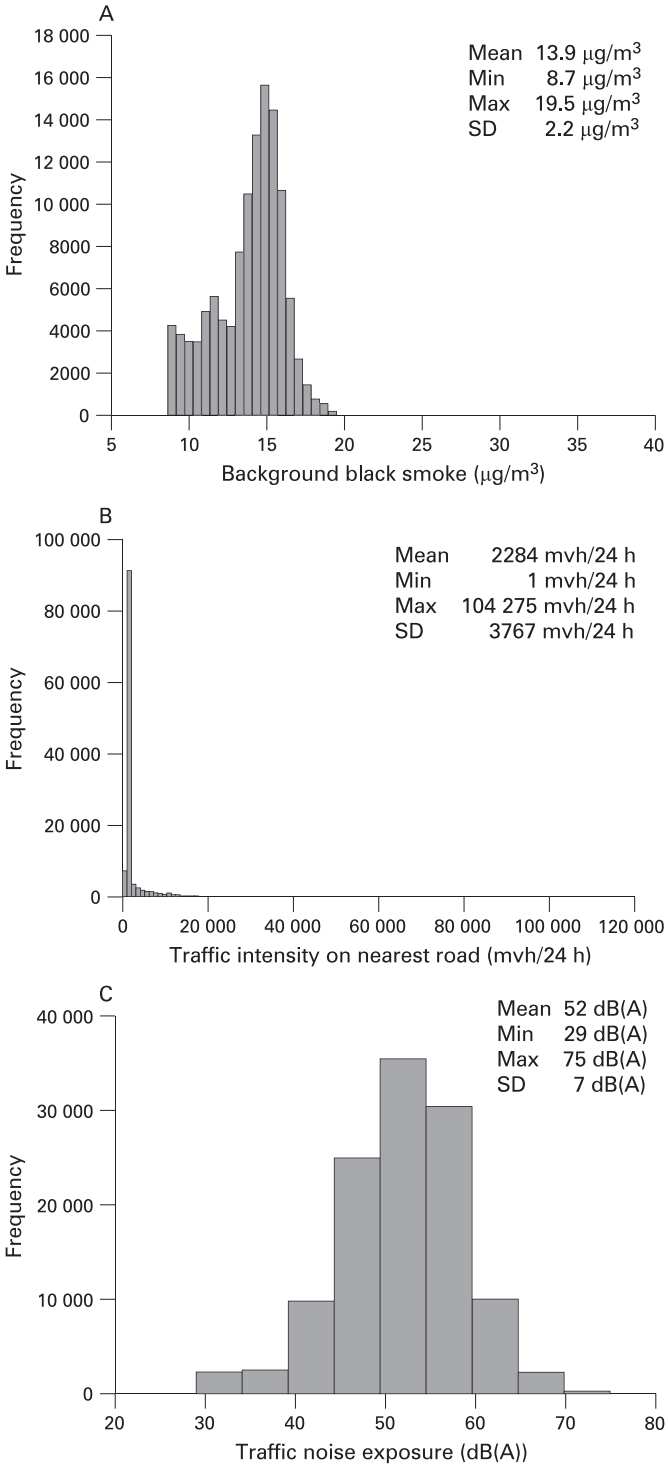

Figure 1 Distribution of estimated background black smoke concentrations (1987–1996), traffic intensity on the nearest road and traffic noise exposure at the 1986 home address (n = 117 528). dB(A), A-weighted average sound pressure decibel levels; mvh/24 h, motor vehicles/24 h.

background black smoke, 1.07 (95% CI 1.01 to 1.14) for traffic intensity on nearest road and 1.13 (95% CI 0.92 to 1.39) for the highest noise category.

Additional analyses

When traffic intensity on the nearest road was modelled as a categorical variable, elevated relative risks were found for the category >10 000 mvh/24 h for cardiovascular (1.12 (95% CI 0.99 to 1.28)) and IHD mortality (1.24 (95% CI 1.05 to 1.46)) (table 4). The associations for traffic intensity on the nearest road as a categorical variable were insensitive to adjustment for traffic noise. After adjustment for background black smoke and traffic intensity as a categorical variable, relative risks for traffic noise showed a similar pattern as when traffic intensity was modelled as a continuous variable.

Relative risks for IHD mortality were somewhat elevated for living near a major road (1.15 (95% CI 0.99 to 1.34)) and for traffic intensity in a 100 m buffer (1.05 (95% CI 0.95 to 1.16)) (table 4).

Relative risks for background NO_2 and $PM_{2.5}$ concentrations were elevated for cerebrovascular and heart failure mortality (table 4), which is comparable with the results for background black smoke.

The relative risks for traffic noise were essentially unity when traffic noise was included as a continuous exposure variable. Relative risks for background black smoke and traffic intensity on the nearest road were not affected (data not shown).

After excluding the subjects with noise exposure >65 dB(A), effect estimates for cardiovascular mortality for background black smoke did not change, whereas they slightly increased for traffic intensity on the nearest road from 1.05 (95% CI 0.99 to 1.12) to 1.09 (95% CI 1.02 to 1.17). These analyses were conducted to evaluate the independent air pollution effects in subjects with traffic noise levels for which no noise effects have been found.

After excluding the subjects without traffic intensities (~80% of the subjects), the multivariate relative risks changed slightly, with relative risks for cardiovascular mortality of 1.08 (95% CI 1.00 to 1.17) for traffic intensity on the nearest road and 1.21 (95% CI 0.89 to 1.66) for the highest noise category. Similar to the main analyses, the relative risk for the highest noise category decreased when background black smoke and traffic intensity were included in the model from 1.34 (95% CI 0.99 to 1.80) to 1.21 (95% CI 0.89 to 1.66).

Effect estimates of background black smoke, traffic intensity and noise for cardiovascular mortality did not differ between men and women, between subjects aged <62 years and subjects aged >62 years, between never, ex and current cigarette smokers, or between groups with different percentages of people with a low income in their neighbourhood (results not shown).

DISCUSSION

For the first time, the joint association between long-term exposure to air pollution, traffic intensity and road traffic noise with cardiovascular mortality has been reported. Background black smoke concentrations, traffic intensity on the nearest road and traffic noise above 65 dB(A) were associated with specific cardiovascular causes of death. Associations with background black smoke and traffic intensity were insensitive to noise adjustment. Exclusion of observations with traffic noise above 65 dB(A), the only noise category for which some effect was found, did slightly increase the effect estimate for traffic intensity. After adjustment for black smoke concentrations and traffic intensity, traffic noise risks estimates became unity for IHD mortality, while the noise risk for heart failure mortality was more robust and was only slightly reduced.

Traffic noise and air pollution

The moderate correlation of modelled traffic noise with background black smoke (0.24) and traffic intensity on the

Table 3 Adjusted relative risks (95% CI) for association between overall cardiovascular mortality and more specific cardiovascular mortality causes, and background black smoke (continuous), traffic intensity on the nearest road (continuous) and traffic noise exposure (in categories) assessed separately and together*

Model	Exposure	Cardiovascular (n = 6137), RR (95% CI)	Ischaemic heart disease (n = 3521), RR (95% CI)	Cerebrovascular (n = 1175), RR (95% CI)	Heart failure (n = 422), RR (95% CI)	Cardiac dysrhythmia (n = 339) RR (95% CI)
Air pollution indicators	Background black smoke	1.11 (0.96 to 1.28)	1.01 (0.83 to 1.22)	1.39 (0.99 to 1.94)	1.75 (1.00 to 3.05)	0.96 (0.51 to 1.79)
	Traffic intensity on nearest road	1.05 (0.99 to 1.12)	1.11 (1.03 to 1.20)	0.82 (0.68 to 1.00)	1.07 (0.86 to 1.34)	1.04 (0.79 to 1.36)
Traffic noise exposure	Traffic noise 50–55 dB(A)	1.00 (0.94 to 1.07)	1.00 (0.92 to 1.09)	0.90 (0.78 to 1.04)	1.08 (0.85 to 1.38)	1.03 (0.78 to 1.36)
	Traffic noise 55–60 dB(A)	1.00 (0.93 to 1.08)	1.02 (0.93 to 1.12)	0.89 (0.76 to 1.05)	1.00 (0.76 to 1.32)	1.08 (0.80 to 1.46)
	Traffic noise 60–65 dB(A)	0.91 (0.81 to 1.03)	0.95 (0.82 to 1.11)	0.59 (0.43 to 0.80)	1.04 (0.67 to 1.61)	1.08 (0.67 to 1.72)
	Traffic noise >65 dB(A)	1.25 (1.01 to 1.53)	1.15 (0.86 to 1.53)	0.88 (0.52 to 1.50)	1.99 (1.05 to 3.79)	1.23 (0.50 to 3.01)
Both air pollution indicators and traffic noise exposure	Background black smoke	1.11 (0.95 to 1.28)	1.01 (0.83 to 1.22)	1.41 (1.01 to 1.97)	1.76 (1.01 to 3.08)	0.94 (0.50 to 1.76)
	Traffic intensity on nearest road	1.06 (0.99 to 1.13)	1.12 (1.04 to 1.21)	0.90 (0.74 to 1.10)	1.02 (0.79 to 1.32)	1.01 (0.75 to 1.36)
	Traffic noise 50–55 dB(A)	1.00 (0.94 to 1.07)	1.00 (0.91 to 1.09)	0.90 (0.78 to 1.04)	1.07 (0.83 to 1.37)	1.03 (0.78 to 1.36)
	Traffic noise 55–60 dB(A)	0.99 (0.92 to 1.06)	1.00 (0.91 to 1.10)	0.89 (0.76 to 1.05)	0.97 (0.73 to 1.29)	1.09 (0.80 to 1.47)
	Traffic noise 60–65 dB(A)	0.88 (0.78 to 1.00)	0.90 (0.76 to 1.06)	0.61 (0.44 to 0.84)	1.01 (0.64 to 1.59)	1.07 (0.66 to 1.76)
	Traffic noise >65 dB(A)	1.17 (0.94 to 1.45)	1.01 (0.74 to 1.36)	0.95 (0.55 to 1.66)	1.90 (0.96 to 3.78)	1.23 (0.48 to 3.13)

*Adjusted for age, gender, smoking status and area level indicators of socio-economic status.
Relative risks for continuous variables were calculated for changes from the 5th to the 95th percentile, for black smoke (10 $\mu g/m^3$ increment) and for traffic intensity on the nearest road (10 000 mvh/24 h increment). Relative risks for traffic noise in categories were calculated with category $\leqslant$50 dB(A) as reference category. dB(A), A-weighted average sound pressure decibel levels; n, number of cases; RR, relative risk.

nearest road (0.30) allowed their independent effects to be assessed. Traffic on other nearby roads was included in the noise model. However, the correlation between traffic intensity within a 100 m circle around the home and noise was only slightly larger (0.38). The observed correlations between modelled traffic noise and air pollution were only slightly lower than in Oslo between modelled noise and air pollution at 0.46 for NO_2 and 0.46 for residential traffic intensity.[23] In addition, the correlation between measured traffic noise and NO_2 was 0.35 in Madrid[24] and 0.53 in an urban area in Canada.[25] Although traffic intensity is an important input variable for the model, other variables such as road surface, location of noise barriers and traffic speed are also included in the noise model.[19] The inclusion of these input variables likely explains the moderate correlation between modelled traffic noise and traffic intensity on the nearest road. Road surface and noise barriers affect noise much more than air pollution.[19] Traffic speed also affects air pollution and noise emissions differently. For example, within urban areas, air pollution emissions decrease when speed increases and congestion is less, whereas noise emissions increase in the same situation.[26 27] The distance decay function used in the noise model differs from air pollution (larger impacted area, beyond first line of buildings). Further, noise levels behave very robustly to increases in traffic intensity, which may also explain the moderate correlation. Doubling of road traffic intensity results in just a 3 dB(A) higher average noise level.[10]

Limitations of the exposure assessment for air pollution and noise have to be considered. Exposure was assessed for the 1986 address. It was estimated that 90% of the participants had lived for 10 years or longer, with mean duration of residence of 35 years (SD 19.8), at their 1986 address before follow-up,[5] and 70% of the participants did not move between 1986 and the end of follow-up.[12] Mean traffic noise levels and the percentage of subjects exposed to the highest noise category did not differ between movers and non-movers, which does not suggest that differential moving due to noise exposure occurred. Information about moving was only available for a subset of the full cohort,

Table 4 Adjusted relative risks (95% confidence intervals) for association between overall cardiovascular mortality and more specific cardiovascular mortality causes, with background NO_2 and $PM_{2.5}$, and traffic variables: traffic intensity on nearest road in categories, indicator variable for living near a major road and traffic intensity in a 100 m buffer*

Exposure	Cardiovascular (n = 6137), RR (95% CI)	Ischaemic heart disease (n = 3521), RR (95% CI)	Cerebrovascular (n = 1175), RR (95% CI)	Heart failure (n = 422), RR (95% CI)	Cardiac dysrhythmia (n = 339), RR (95% CI)
Background concentrations					
Background NO_2	1.08 (0.94 to 1.26)	0.97 (0.80 to 1.18)	1.51 (1.07 to 2.12)	1.96 (1.11 to 3.46)	1.05 (0.56 to 1.95)
Background $PM_{2.5}$	1.11 (0.93 to 1.33)	0.96 (0.75 to 1.22)	1.62 (1.07 to 2.44)	2.69 (1.37 to 5.27)	0.66 (0.30 to 1.45)
Traffic variables					
Traffic intensity on nearest road					
1225–10 000 mvh/24 h	0.96 (0.88 to 1.03)	0.98 (0.89 to 1.09)	0.90 (0.75 to 1.07)	0.92 (0.69 to 1.24)	1.03 (0.75 to 1.41)
>10 000 mvh/24 h	1.11 (0.99 to 1.25)	1.21 (1.04 to 1.42)	0.75 (0.55 to 2.03)	1.36 (0.90 to 2.05)	1.10 (0.66 to 1.84)
Living near a major road	1.05 (0.93 to 1.18)	1.15 (0.99 to 1.34)	0.70 (0.51 to 0.96)	0.94 (0.59 to 1.49)	1.13 (0.70 to 1.82)
Traffic intensity in 100 m buffer	1.00 (0.92 to 1.08)	1.05 (0.95 to 1.16)	0.81 (0.67 to 0.99)	0.97 (0.72 to 1.32)	1.07 (0.77 to 1.48)

*Adjusted for age, gender, smoking status and area level indicators of socio-economic status.
Relative risks were calculated for changes from the 5th to the 95th percentile: for NO_2 30 $\mu g/m^3$, for $PM_{2.5}$ 10 $\mu g/m^3$, and for traffic intensity in a 100 m buffer 335 000 mvh/24 h. Relative risks for traffic intensity on nearest road in categories were calculated with $\leqslant$1225 mvh/24 h as reference category. Relative risks for living near a major road were calculated with not living near a major road as reference category. Models for traffic variables included background black smoke (1987–1996). mvh, motor vehicles; n, number of cases; NO_2, nitrogen dioxide; $PM_{2.5}$, fine particles less than 2.5 μm in diameter; RR, relative risk.

and therefore an analysis restricted to non-movers was not possible. We previously showed that relative risks among non-movers increased for the association between black smoke concentrations and mortality.[12] Further, concentrations for the periods 1976–1985 and 1987–1996 were highly correlated (>0.9).[18] These results support the use of our exposure estimate as a proxy for other time periods.

Traffic noise was estimated using traffic data from 2000–2001, whereas exposure was estimated for the 1986 address. This is likely not a major problem because traffic intensities for the period 1986–1996 were highly correlated (>0.9).[18] Correlations between traffic intensities for 1986 and 1997–2001 were high as well (>0.87). Traffic intensities have increased over this period, mainly on motorways and in new urban areas.[18] The increases on motorways have in general been compensated by measures to reduce (additional) noise. Therefore, we use the assumption that while absolute traffic intensities may have changed, relative differences are likely to be stable and busy roads with high traffic noise levels stayed busy during this time period. Further, we focused mainly on busy roads that most probably already existed between 1987 and 2001.[18]

We had no information about the time people spend at home or information about the work address. However, approximately 85% of the population had no paid job at baseline as most women did not have a job at baseline and some of the men below 65 years of age also had no job at baseline.

Traffic noise exposure was estimated as the maximum level of the yearly average equivalent noise levels during the day, evening or night. The levels during the evening and night received a penalty of 5 and 10 dB(A), respectively. Other studies analysed daytime or 24 h exposures and our modelled noise levels may on average be 1–5 dB(A) higher. Correlations between indicators for long-term exposure to equivalent noise levels from road traffic are however high,[10] since traffic flows during the day, evening and night are highly correlated. So the use of different indicators affects the risk observed at a certain noise level but is unlikely to influence the associations. Due to the high correlation, it is difficult to distinguish the separate effects on mortality of noise exposure during the day, evening and night when information on room orientation is not available. Information about other characteristics of the noise exposure, such as the number of events, was not available in our study.

We did not have information about mediating factors such as bedroom location, window opening habits or sound insulation. Studies have shown that noise effects were larger when such mediating factors were considered in the analyses.[10] The implication is that the effect of true noise exposure (indoors) may be underestimated. However, for the population studied the associations with traffic intensity remained and are unlikely due to environmental noise levels possibly because of the exposure reduction strategies listed above. The difference between noise exposure and noise environmental levels may be different in other cities or populations.

Elevated risks for the effects of traffic noise on cardiovascular mortality were restricted to the highest noise category (>65 dB(A)), but only 1.6% of our participants were exposed to such noise levels. Subjects lived on average for a long time at their baseline address and were therefore exposed to similar noise levels over this period. From a biological point of view one would expect a continuous increase in risk with increasing noise level. However, other studies that assessed the exposure–effect relationships of noise on cardiovascular effects also showed a threshold of effect,[10] possibly due to physiological adaptation and coping.

A recent Dutch study investigated road traffic noise and hypertension, adjusting for fine particle (PM_{10}) exposure.[28] However, variation in exposure to PM_{10} was limited and this might be one of the explanations why there was no significant contribution to the relative risk for PM_{10}.

Specific causes of cardiovascular death

A few cohort studies evaluated the effects of long-term exposure to air pollution on specific causes of cardiovascular mortality, which can be compared with our results for the background black smoke concentration. Pope *et al* found an elevated relative risk of 1.12 (95% CI 1.08 to 1.15) for all cardiovascular diseases plus diabetes for a 10 μg/m^3 increase in $PM_{2.5}$ concentrations. Relative risks were 1.18 (95% CI 1.14 to 1.23) for IHD and 1.13 (95% CI 1.05 to 1.21) for dysrhythmia, heart failure and cardiac arrest. No elevated risk was found for cerebrovascular disease.[13] A large cohort study among US women found increased risks for overall cardiovascular mortality (RR 1.76 (95% CI 1.25 to 2.47)) and for coronary heart disease (RR 2.21 (95% CI 1.17 to 4.16)) for a 10 μg/m^3 increase in $PM_{2.5}$ exposure.[4] In contrast with the Pope *et al* study,[13] cerebrovascular mortality was also significantly associated with exposure to $PM_{2.5}$ in this US study[4] as in our study. In a small cohort of Norwegian men no association between cerebrovascular mortality and NO_x was found, whereas IHD mortality was significantly associated with a 10 μg/m^3 increase in NO_x concentrations (RR 1.08 (95% CI 1.03 to 1.12)).[7] In general, an association with overall cardiovascular mortality was found. However, results for more specific cardiovascular causes varied between studies. Varying results between studies may be explained by differences in used exposure assessment methods (average concentration for a city versus individual-level traffic-related exposure) and in the air pollutants used (traffic-related pollutants versus less traffic-related pollutants). Different types of air pollution may have different mechanisms of effect. In none of these studies were the results for air pollution adjusted for noise from road traffic.

Recent epidemiological studies have increased understanding of the linkage between air pollution and cardiovascular diseases, with a multitude of plausible mechanistic explanations having been demonstrated experimentally during the past few years.[29] The physical and chemical characteristics of fresh vehicle exhaust particles are different from those of background particles influenced by atmospheric transformation and coagulation. This may affect the mechanisms of effect. The proposed biological mechanisms linking air pollution to cardiovascular disease involve direct effects of pollutants on the cardiovascular system, blood and lung receptors, and/or indirect effects mediated through oxidative stress and inflammation.[30] A cascade of physiological responses may follow, including alterations in blood rheology, cardiac dysrhythmias and the development of atherosclerosis.[30] Studies have shown associations between air pollution exposure and ST-depression, which possibly represents myocardial ischaemia or inflammation.[31 32] These findings suggest that ischaemic mechanisms may explain the specific association between traffic exposure and IHD. Cerebrovascular mortality is more likely due to a thrombotic process,[33] and possibly components of the background mixture are more related to thrombosis. However, the mechanisms of effect are not yet exactly known and all the mechanisms are likely inter-related.

Traffic intensity near the home address was only associated with IHD mortality in our study. Sensitivity analyses showed

that the association was restricted to the highest traffic intensity category (>10 000 mvh/24 h). A recent study by Tonne *et al* found an association between cumulative traffic near the home and acute myocardial infarction.[9] Peters *et al* also found an association between exposure to traffic and acute myocardial infarction.[14] A German cross-sectional study found that living within 150 m of a major road was associated with the prevalence of coronary heart disease (odds ratio 1.85 (95% CI 1.21 to 2.84)).[8] The results of a study by Rosenlund *et al* also suggested that residential traffic-related air pollution increases the risk of coronary heart disease, and in particular fatal outcomes.[34] The results of these studies suggest that traffic intensity is especially associated with IHD. Our results also suggested an association between IHD and traffic intensity.

Several epidemiological studies investigated the effects of road traffic noise exposure on different cardiovascular endpoints. Inconsistent effects were found for blood pressure and hypertension, but the evidence for IHD is much stronger.[10] Cohort and case-control studies in Caerphilly, Speedwell and Berlin found relative risks for IHD ranging from 1.1 to 1.4, although non-significant, at traffic noise levels above 60 dB(A).[35–37] Our IHD risk estimate is in line with these results. The strongest noise effects in our study were found for heart failure mortality, but this association was based upon a small number of cases and has not been evaluated in previous studies. The suggested effect mechanism of noise is based on the general stress concept and works "directly" through synaptic nervous interactions and "indirectly" through the emotional and the cognitive perception of noise. Stress can result in changes in physiological functions and metabolism, including blood pressure, cardiac output, blood lipids, carbohydrates, electrolytes, blood clotting factors, leukocyte count and others. These can be acute changes, but in the long term functional changes and dysregulation may occur, thus increasing the risk of manifest diseases. Since many of these factors are known classic cardiovascular risk factors, chronic noise exposure can increase the risk of cardiovascular disease such as IHD.[10 11]

Death certificates may not be a perfect source of information for cause of mortality.[38] There may be a convergence towards the most common cardiovascular causes of death and the utility of death certificates may decrease when death occurs at an older age.[39] There is no recent information on the validity of death certification in The Netherlands. It is possible that misclassification of specific cardiovascular causes on death certificates contributes to the inconsistency of results between different studies.

Both individual and area-level socio-economic characteristics have been shown to be predictors of cardiovascular health.[40] We adjusted for area-level socio-economic characteristics, but not at the individual level which was only available for the case-cohort dataset. Analyses in the case-cohort dataset showed, however, that individual-level socio-economic characteristics did not confound the association.[12] Of the area-level indicators of socio-economic status, in particular the percentages of persons with low and high incomes in a neighbourhood were significantly associated with mortality. As air pollution is one mechanism through which low neighbourhood socio-economic status may affect mortality, we may have been over-adjusting the effects of air pollution. We cannot exclude the possibility that traffic intensity is associated with unmeasured risk factors other than air pollution and noise.

In conclusion, background black smoke concentrations, traffic intensity on the nearest road and traffic noise above 65 dB(A) were associated with specific cardiovascular causes of death. Associations with background black smoke and traffic intensity were insensitive to noise adjustment. Associations with traffic noise became unity for IHD mortality and slightly reduced for heart failure mortality after adjustment for background black smoke and traffic intensity on the nearest road. As this is the first study that has reported the effects of long-term exposure to air pollution, traffic intensity and traffic noise on mortality together in one study, further studies are required to confirm or refute our findings.

Main messages

- Motorised traffic is an important source of both air pollution and noise.
- This study has reported for the first time the joint association between long-term exposure to air pollution, traffic intensity and road traffic noise with cardiovascular mortality.
- Background black smoke concentrations, traffic intensity on the nearest road and traffic noise above 65 dB(A) were associated with specific cardiovascular causes of death.
- However, associations between black smoke concentrations and traffic intensity on the nearest road with specific cardiovascular causes of death were insensitive for adjustment by traffic noise and were thus not explained by traffic noise in this study.

Policy implications

Traffic-related air pollution is associated with cardiovascular mortality, while the independent contribution of exposure to traffic-related noise is less clear.

Acknowledgements: We wish to thank the Dutch Central Bureau of Genealogy and the Dutch Central Bureau of Statistics for providing data. We thank the co-workers of the NLCS study (Maastricht University/TNO) for assistance. We thank Carla van Wiechen, Wim Swart (National Institute of Public Health and the Environment), Ton Dassen and Hans Nijland (Netherlands Environmental Assessment Agency) for advice on geographical information system calculations and noise modelling. We thank the National Institute of Public Health and the Environment for providing air pollution data monitored by the National Air Quality Monitoring Network in the Netherlands.

Funding: Research described in this article was conducted under contract to the Health Effects Institute (HEI) (research grant 01–2), an organisation jointly funded by the United States Environmental Protection Agency (EPA) and certain motor vehicle and engine manufacturers. The contents of this article do not necessarily reflect the views of HEI, or its sponsors, nor do they necessarily reflect the views and policies of the EPA or motor vehicle and engine manufacturers. The Netherlands Cohort Study on Diet and Cancer is supported by the Dutch Cancer Society.

Competing interests: None.

Ethics approval: The NLCS study was approved by institutional review boards from Maastricht University and the Netherlands Organization for Applied Scientific Research (TNO).

REFERENCES

1. **Dockery DW,** Pope CA III, Xu X, *et al*. An association between air pollution and mortality in six U.S. cities. *N Engl J Med* 1993;**329**:1753–9.
2. **Pope CA 3rd,** Burnett RT, Thun MJ, *et al*. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA* 2002;**287**:1132–41.
3. **Pope CA III,** Thun MJ, Namboodiri MM, *et al*. Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults. *Am J Respir Crit Care Med* 1995;**151**:669–74.
4. **Miller KA,** Siscovick DS, Sheppard L, *et al*. Long-term exposure to air pollution and incidence of cardiovascular events in women. *N Engl J Med* 2007;**356**:447–58.
5. **Hoek G,** Brunekreef B, Goldbohm S, *et al*. Association between mortality and indicators of traffic-related air pollution in the Netherlands: a cohort study. *Lancet* 2002;**360**:1203–9.

6. **Gehring U,** Heinrich J, Kramer U, *et al*. Long-term exposure to ambient air pollution and cardiopulmonary mortality in women. *Epidemiology* 2006;**17**:545–51.
7. **Nafstad P,** Haheim LL, Wisloff T, *et al*. Urban air pollution and mortality in a cohort of Norwegian men. *Environ Health Perspect* 2004;**112**:610–15.
8. **Hoffmann B,** Moebus S, Stang A, *et al*. Residence close to high traffic and prevalence of coronary heart disease. *Eur Heart J* 2006;**27**:2696–702.
9. **Tonne C,** Melly S, Mittleman M, *et al*. A case-control analysis of exposure to traffic and acute myocardial infarction. *Environ Health Perspect* 2007;**115**:53–7.
10. **Babisch W.** Transportation noise and cardiovascular risk: updated review and synthesis of epidemiological studies indicate that the evidence has increased. *Noise Health* 2006;**8**:1–29.
11. **van Kempen EE,** Kruize H, Boshuizen HC, *et al*. The association between noise exposure and blood pressure and ischemic heart disease: a meta-analysis. *Environ Health Perspect* 2002;**110**:307–17.
12. **Beelen R,** Hoek G, van den Brandt PA, *et al*. Long-term effects of traffic-related air pollution on mortality in a Dutch cohort. *Environ Health Perspect* 2008;**116**:196–202.
13. **Pope CA 3rd,** Burnett RT, Thurston GD, *et al*. Cardiovascular mortality and long-term exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease. *Circulation* 2004;**109**:71–7.
14. **Peters A,** von Klot S, Heier M, *et al*. Exposure to traffic and the onset of myocardial infarction. *N Engl J Med* 2004;**351**:1721–30.
15. **van den Brandt PA,** Goldbohm RA, van't Veer P, *et al*. A large-scale prospective cohort study on diet and cancer in The Netherlands. *J Clin Epidemiol* 1990;**43**:285–95.
16. **Volovics A,** van den Brandt P. Methods for the analyses of case-cohort studies. *Biom J* 1997;**39**:195–214.
17. **van den Brandt PA,** Schouten LJ, Goldbohm RA, *et al*. Development of a record linkage protocol for use in the Dutch cancer registry for epidemiological research. *Int J Epidemiol* 1990;**19**:553–8.
18. **Beelen R,** Hoek G, Fischer P, *et al*. Estimated long-term outdoor air pollution concentrations in a cohort study. *Atmos Environ* 2007;**41**:1343–58.
19. **Dassen A,** Jabben J, Janssen P. *Development and optimalization of the National Noise Nuisance Overview - partial validation and sensitivity analysis (Uitbouw en optimalisatie van het Landelijk Beeld van Verstoring - Partiele validatie en gevoeligheidsanalyse)*. Bilthoven: RIVM, 2001.
20. **Ministry of Housing, Spatial Planning and the Environment**. *Calculation and measurement regulation -road traffic noise (Reken- en meetvoorschrift wegverkeerslawaai)*. The Hague: Staatscourant, 2002:62.
21. **European Commission**. Directive of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. Directive 2002/49/EC. *Official Journal of the European Communities* 2002;**189**:12–25.
22. **DerSimonian R,** Laird N. Meta-analysis in clinical trials. *Control Clin Trials* 1986;**7**:177–88.
23. **Klaeboe R,** Kolbenstvedt M, Clench-Aas J, *et al*. Oslo traffic study - part 1: an integrated approach to assess the combined effect of noise and air pollution on annoyance. *Atmos Environ* 2000;**34**:4727–36.
24. **Tobias A,** Diaz J, Saez M, *et al*. Use of Poisson regression and Box-Jenkins models to evaluate the short-term effects of environmental noise levels on daily emergency admissions in Madrid, Spain. *Eur J Epidemiol* 2001;**17**:765–71.
25. **Vlaanderen J,** Davies H, Henderson S, *et al*. Correlation between co-exposures to noise and air pollution from traffic sources. *Epidemiology* 2006;**17**:S251–S252.
26. **Beevers SD,** Carslaw DC. The impact of congestion charging on vehicle emissions in London. *Atmos Environ* 2005;**39**:1–5.
27. **Lelong J,** Michelet R. Effect of acceleration on vehicle noise emission. Presented at Forum Acoustica, Berlin, 1999.
28. **de Kluizenaar Y,** Gansevoort RT, Miedema HME, *et al*. Hypertension and road traffic noise exposure. *J Occup Environ Med* 2007;**49**:484–92.
29. **Brook RD.** Is air pollution a cause of cardiovascular disease? Updated review and controversies. *Rev Environ Health* 2007;**22**:115–37.
30. **Brook RD,** Franklin B, Cascio W, *et al*. Air pollution and cardiovascular disease: a statement for healthcare professionals from the Expert Panel on Population and Prevention Science of the American Heart Association. *Circulation* 2004;**109**:2655–71.
31. **Pekkanen J,** Peters A, Hoek G, *et al*. Particulate air pollution and risk of ST-segment depression during repeated submaximal exercise tests among subjects with coronary heart disease: the Exposure and Risk Assessment for Fine and Ultrafine Particles in Ambient Air (ULTRA) study. *Circulation* 2002;**106**:933–8.
32. **Gold DR,** Litonjua AA, Zanobetti A, *et al*. Air pollution and ST-segment depression in elderly subjects. *Environ Health Perspect* 2005;**113**:883–7.
33. **Bath PM,** Lees KR. ABC of arterial and venous disease. Acute stroke. *BMJ* 2000;**320**:920–3.
34. **Rosenlund M,** Picciotto S, Forastiere F, *et al*. Traffic-related air pollution in relation to incidence and prognosis of coronary heart disease. *Epidemiology* 2008;**19**:121–8.
35. **Babisch W,** Ising H, Elwood PC, *et al*. Traffic noise and cardiovascular risk: the Caerphilly and Speedwell studies, second phase. Risk estimation, prevalence, and incidence of ischemic heart disease. *Arch Environ Health* 1993;**48**:406–13.
36. **Babisch W,** Ising H, Gallacher JE, *et al*. Traffic noise and cardiovascular risk: the Caerphilly and Speedwell studies, third phase--10-year follow up. *Arch Environ Health* 1999;**54**:210–16.
37. **Babisch W,** Beule B, Schust M, *et al*. Traffic noise and risk of myocardial infarction. *Epidemiology* 2005;**16**:33–40.
38. **Lloyd-Jones DM,** Martin DO, Larson MG, *et al*. Accuracy of death certificates for coding coronary heart disease as the cause of death. *Ann Intern Med* 1998;**129**:1020–6.
39. **Goldacre MJ.** Cause-specific mortality: understanding uncertain tips of the disease iceberg. *J Epidemiol Community Health* 1993;**47**:491–6.
40. **Diez-Roux AV,** Merkin SS, Arnett D, *et al*. Neighborhood of residence and incidence of coronary heart disease. *New Engl J Med* 2001;**345**:99–106.