PRESENCIA DE METALES PESADOS EN ÁREAS URBANAS DE CHILE

Heavy metal in urban areas of Chile

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CONTENIDO

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INTRODUCCIÓN

En la actualidad, no cabe la menor duda de que el cuidado del ambiente no sólo significa la conservación y preservación de especies sobre el planeta, sino la salvación misma de él y de los seres vivos que lo habitan. A nivel nacional, la temática ha ganado adherentes rápidamente y los científicos debemos responder a esta situación, en una forma organizada, efectiva y eficiente.

El problema acuciante de la contaminación de algunas áreas en el país, debe ser atacado con prontitud, pero además se debe realizar acciones que consideren los riesgos potenciales a mediano y largo plazo, de modo que se impida una vuelta atrás al cabo de pocos años.

Los metales pesados, la mayoría de los cuales son adicionados al ambiente por acciones no naturales, pueden constituirse en contaminantes que generen graves problemas en el corto, mediano y largo plazo. Por lo tanto, deben ser cuidadosamente cuantificados y estudiados en su comportamiento una vez que han ingresados al ambiente.

Las áreas urbanas, en tanto que centros con altas cifras de población, están sujetas a una potencial contaminación de sus suelos, aguas y aire, derivada tanto de la actividad natural de los seres humanos, como de las actividades industriales y de servicios que complementan la vida urbana.

En este trabajo, el foco de atención se centra en los metales pesados presentes en el aire o detectados en otros medios, pero sin duda transportados hasta ellos a través del aire. En especial, se entregarán resultados obtenidos en la ciudad de Santiago, fundamentalmente debido a la escasez de información existente para otras ciudades del país.

ANTECEDENTES GENERALES

Para el estudio de los elementos traza, en especial metales pesados, es necesario entender primeramente algunos conceptos básicos sobre el substrato en el cual se encuentran dichos elementos en el aire. En líneas generales, en el aire se pueden distinguir dos grandes tipos de contaminantes: los gases, cualquiera sea su naturaleza química (orgánica o inorgánica) y el material particulado suspendido, denominado también aerosoles atmosféricos o simplemente, partículas. Este trabajo se refiere específicamente al segundo tipo de contaminantes, en el cual se detecta la presencia en el aire de los metales pesados.

Relación tamaño del aerosol-impacto sobre la salud

Los aerosoles atmosféricos se presentan en una amplia gama de tamaños, forma y composición química. Con respecto al tamaño y para nuestros efectos, los aerosoles atmosféricos presentan diámetros que se sitúan entre los 45 y los 0,01 μm. Para el establecimiento de las normas, esto es, de las concentraciones máximas que pueden estar presentes en el aire, sin causar daño a la salud humana, interesan sólo las concentraciones totales de los aerosoles de tamaños < 45 μm y < 10 μm. Estos últimos se denominan, también, la "fracción inhalable" del aerosol, o sea, aquella capaz de penetrar en el aparato respiratorio.

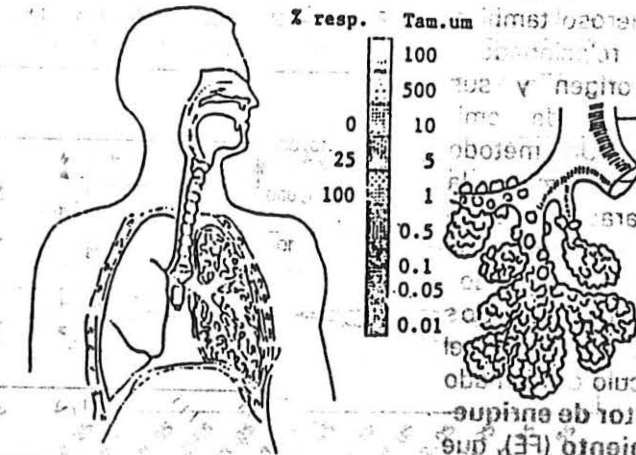


Figura 1. Esquema del aparato respiratorio, indicando cualitativamente la penetración del aerosol, según tamaño y porcentaje de respirabilidad para aerosoles < 10 µm

Es importante enfatizar que dichas normas son determinadas considerando la salud humana y se denominan normas primarias. Cuando se trata de la protección del ambiente (suelos, aguas, plantas, etc.), los valores de las normas son bastante menores, esto es mucho más exigentes, y en Chile no existen; se trata de las normas secundarias.

Desde el punto de vista de la salud humana y debido a la estructura del aparato respiratorio, es muy importante el conocimiento de las concentraciones del aerosol en sus distintos tamaños bajo los 10 μm y sus correspondientes composiciones químicas. Esto resulta del hecho de que esos aerosoles pueden penetrar hasta diferentes niveles del aparato respiratorio, alcanzando mayor profundidad en la medida que presentan menores diámetros.

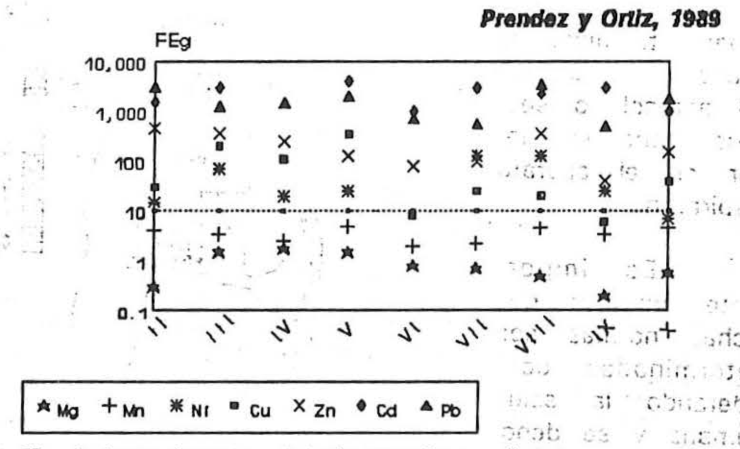
La **Figura 1** muestra cualitativa y cuantitativamente la situación anterior (**Préndez et al., 1991**). Se aprecia que, estrictamente, las partículas < 45 μm y hasta 10 μm, carecen de interés desde el punto de vista salud. Pero, en la medida que sus diámetros disminuyen bajo los 10 μm, su penetración al organismo es cada vez mayor. El aerosol de 10 μm, prácticamente, no se retiene en el aparato respiratorio, pues es rápidamente reexpelido hacia afuera de él. Los porcentajes de retención de las partículas aumentan a medida que, por su aún menor tamaño, ellas son capaces de alcanzar las zonas no ciliadas del aparato respiratorio, esto es, los pulmones y los alvéolos pulmonares, situación que ocurre ya para partículas de diámetro < 3 μm.

A estas profundidades del aparato respiratorio, la remoción de las partículas es muy difícil, de modo que ellas pueden permanecer dentro de los pulmones por largo tiempo. Este hecho es particularmente importante cuando se agrega al tamaño de la partícula, su composición química y con ello, su potencial toxicidad.

Relación tamaño del aerosol-origen y fuentes de emisión

El tamaño del aerosol también está relacionado a su origen y sus fuentes de emisión. Un método que permite la separación entre los elementos de origen natural y los antropogénicos está dado por el cálculo del llamado **factor de enriquecimiento (FE)**, que se obtiene haciendo una cierta razón entre las concentraciones de los elementos en estudio, de forma relativa a un elemento tomado como referencia.

FIGURA 2. FEg PARA Mg, Mn, Ni, Cu, Zn, Cd y Pb, EN AEROSOLES DE DISTINTOS LUGARES DE SANTIAGO



FEg= factores de enriquecimiento promedio geométrico

Dicho valor suele situarse en el rango entre 1 y 10 aproximadamente, para los elementos de origen natural. Valores superiores indican que los elementos se encuentran enriquecidos en el aire por los respectivos aportes desde una fuente de origen antrópico.

La **Figura 2** ejemplifica la utilización de este criterio (**Préndez y Ortiz., 1989**). En ella, se ha representado el FE promedio geométrico (FEg) para diferentes metales pesados cuantificados en el aire, en diferentes sitios de la ciudad de Santiago. El manganeso y el magnesio (no metal pesado, pero sí elemento traza), tienen un factor de enriquecimiento < 10 y por ende son de origen natural.

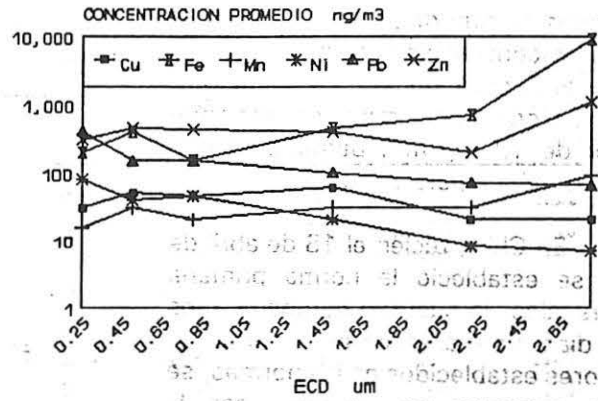
El hierro ha sido elegido como elemento de referencia, pues previamente se ha demostrado su origen natural en Santiago (**Préndez et al., 1984**). Los restantes elementos (níquel, cobre, cinc, plomo y cadmio) presentan FEg > 10 y, en consecuencia, tienen un origen antrópico. Esta conclusión es válida para cualquier zona de la ciudad de Santiago.

Respecto del cobre, es fundamental indicar que, cuando el cálculo de los FE se hace respecto del contenido de cobre de los suelos chilenos y no en función de los promedios internacionales atribuidos a la corteza terrestre, como es la situación generalmente empleada en la literatura, la asignación de su origen cambia de antrópico a natural. Será de esta forma que se le deberá considerar normalmente, en la ciudad de Santiago.

La conclusión anterior es de especial trascendencia cuando se pretende asignar el origen del cobre presente en el aire o a través de él en el suelo, emitido desde una fuente puntual determinada. Por otra parte, esto entrega mayores fundamentos a la posición de que los problemas ambientales sólo pueden resolverse realmente si se conocen adecuadamente el ambiente y sus condiciones naturales, o sea las líneas de base.

FIGURA 3. CONCENTRACIONES PROMEDIO DE Ni, Cu, Pb, Mn, Zn y Fe, EN AEROSOLES ATMOSFERICOS DE SANTIAGO

PRENDEZ Y ORTIZ, 1982



EN FUNCION DEL DIAMETRO DE LA PARTICULA

Por otra parte, las concentraciones de los elementos cambian en una forma que relaciona sus fuentes de emisión y sus diámetros, tal como se ve en la **Figura 3 (Préndez y Ortiz, 1982)**, donde ECD corresponde al diámetro de corte efectivo, que es una forma de expresar el diámetro de las partículas, teniendo en consideración su forma. Se observa que los elementos antropogénicos aumentan sus concentraciones hacia las partículas de menor diámetro. Casos típicos son plomo y níquel.

En cambio, las concentraciones de los elementos naturales aumentan hacia los diámetros mayores. Aquí los casos típicos son hierro y manganeso. Cobre y cinc tienen comportamientos atípicos. El cinc, generalmente emitido en los procesos de incineración, se presenta en diámetros más bien grandes ("fly ash").

De este modo, se cumple también en Santiago, la aseveración comúnmente aceptada de que los aerosoles más pequeños, de 1 a 2 μm o menos, provienen en general de fuentes antrópicas o derivadas de las actividades humanas vinculadas a procesos que ocurren a elevadas temperaturas. La excepción es el fly ash. En cambio, los de mayor tamaño, mayores de 2 μm, tienen un origen natural.

NORMAS

Un problema grave que se suscita para poder evaluar el impacto de los metales pesados contenidos en los aerosoles, es la falta de normativa que oriente al respecto de las concentraciones máximas permitidas, compatibles con la salud de las personas (normas primarias) y con la salvaguarda del ambiente (normas secundarias).

Algunos países tienen reglamentados los contenidos máximos de ciertos metales en el aire, como norma primaria. Sin embargo, no se encuentran normados todos los elementos potencialmente tóxicos y además sus valores no están explícitamente vinculados a la fracción respirable.

El **Cuadro 1** muestra los valores de la norma para plomo, cadmio y vanadio en aerosoles < 45 μm, en algunos países del hemisferio norte. Una característica de las normas es que deben explicitar, además de las concentraciones máximas, los tiempos de exposición. Así, la reglamentación para plomo por ejemplo, corresponde al valor de 1,5 μg m^{-3}, permitido como media aritmética para 3 meses.

Cuadro 1. Normas primarias para algunos metales pesados, en el aire (μg m^{-3})

Elem.	Conc.	Ciudad, País
Pb	1,5	Ciudad de México, Caracas, USA
	0,7	ex URSS
Cd	50	USA
	30	ex URSS
V	50 a 1000	USA
	100	ex URSS

En Chile, recién el 18 de abril de 1994, se estableció la norma primaria para arsénico, la cual fue derogada a los pocos días. Para apreciar la magnitud de los valores establecidos en las normas, se pueden comparar por ejemplo, con la concentración de plomo y cadmio encontrados en los aerosoles de la Antártica chilena **(Cuadro 2)** y que corresponden a los de una atmósfera limpia. Se observa que la norma de plomo, por ejemplo, admite valores 50 a 200 veces superiores al del aire puro. En el caso de cadmio, el rango es entre 3000 y 5000 veces superior.

CONCENTRACIONES DE METALES PESADOS EN AREAS URBANAS

Es usual estimar que las concentraciones de los elementos traza en el aire, están vinculadas a la acción antropogénica y por lo tanto, son mayores en las ciudades que en las áreas rurales y mayores también en las cercanías de fuentes emisoras puntuales.

Cuadro 2. Rango de concentraciones de metales pesados en la península antártica (ng m^{-3}) (Préndez et al., 1993b)

Elem.	Fracción aerosol < 45 μm	Fracción aerosol < 3 μm
Pb	0,017- 0,030	0,0043- 0,136
Cd	0,0 -<0,009	0,0 -<0,002

En el **Cuadro 3**, se dan los valores encontrados para tres ciudades latinoamericanas, haciendo la comparación en función de la fracción del aerosol considerada. Se observa que las concentraciones de diferentes metales pesados, encontradas en la fracción de alta respirabilidad en Santiago y en Sao Paulo son muy similares, pese a que las emisiones en Sao Paulo son del orden de 4 veces mayores a las de Santiago **(Préndez, 1994)**.

Por su parte, la comparación del aerosol total entre Santiago y Caracas muestra valores claramente mayores para nuestra ciudad, a pesar de tener emisiones que son aproximadamente tres veces menores **(Préndez, 1994)**. Particularmente

Cuadro 3. Concentración de metales pesados (ng m^{-3}) en ciudades latinoamericanas

Elem.	Sao Paulo < 4 µm 1984[1]	Santiago < 3 µm 1983[2]	Caracas < 45 µm 1978-1980	Santiago < 45 µm 1976-1983[2]
Pb	1041	1245		1211
Cd		11	<< 20[3]	10
V	340		760[4]	
Hg				6
Mn	129	90	129[3]	115
Zn	1109	596	690	1105
Cu	74	63	60[4]	370
Fe	2099	1468	1880[3]	4102
Cr	260		< 5[4]	75
Ni	19	33	< 80[4]	35
Ti	151			276

[1] Orsini y Boveres, 1980; [2] Información de la autora; [3] Sanhueza et al., 1979; [4] Sanhueza y Lissi, 1980

notables resultan las mayores concentraciones de cinc, cobre y cromo en Santiago.

La comparación con otras ciudades chilenas es difícil, fundamentalmente porque hay muy pocos estudios para ellas. Hacen excepción las ciudades de Antofagasta y Chillán, donde se han cuantificado algunos metales pesados en la fracción del aerosol < 15 µm[1] y las ciudades de Arica (Hrepic et al., 1983) y Rancagua (Alvarez, 1981), para las cuales existe información para la fracción < 45 µm. Los resultados se presenta en el Cuadro 4.

Los estudios efectuados en Arica, con respecto a los metales pesados presentes en la fracción < 45 µm, indican que, de acuerdo al Cuadro 4, en general, las concentraciones no son muy elevadas. Por otra parte, se ha demostrado que cobre, níquel, cinc, plomo y cromo tienen un origen antrópico (Hrepic et al., 1984).

A la situación general, hacen excepción dos casos puntuales, uno referido a las concentraciones de plomo en el aire, proveniente de suelo contaminado en las cercanías de una antigua vía férrea de transporte de mineral y la otra, relativa a la presencia de níquel y plomo y a cinc, emitidos en procesos diferentes por una misma industria de tostación de minerales y arrastrados por los vientos sobre un sector de la ciudad (Hrepic y Quintana, 1990).

Las concentraciones de arsénico en el aire de Rancagua, son varias veces superiores a las detectadas en Santiago, como se deduce al comparar los valores dados en el Cuadro 4, con los valores citados más adelante.

CONCENTRACIONES DE METALES PESADOS EN SANTIAGO

Santiago es la ciudad de Chile que presenta las mayores concentraciones

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[1] J.R. Morales. Comunicación personal

de potenciales contaminantes en el aire y por lo tanto es necesario hacer para ella un análisis más detallado. Un primer aspecto dice relación con los resultados obtenidos para diferentes fracciones del aerosol, mostrados en el **Cuadro 5**. Se destacan los siguientes hechos importantes:

Cuadro 4. Concentraciones promedio de metales pesados (ng m^{-3}) en aerosoles atmosférico <15 y <45 μm, para ciudades chilenas

	Antofag. 1984[1]	Chillán 1983-1990[1]	Arica 1983[2]	Rancagua 1981[3]
	<15 μm		<45 μm	
Ti	106- 109	*	*	
Cr	63- 27	*	*	1 -1197
Mn	9- 2	*	*	*
Fe	100-7191	160 - 326	*	*
Cu	40- 261	*	*	90 - 150
Zn	20- 550	*	675	16 - 642
Pb	*	*	532	200 - 220
Ni	*	*	41	
As	*	*	*	90 - 120
Sb	*	*	*	220 - 430

* No informado; [1] Morales et al., comunicación personal; [2] calculado desde Hrepic et al., 1983; [3] Alvarez, 1981

- en primer lugar, hay que separar los elementos de origen natural, de los antropogénicos; entre los elementos cuantificados, sólo hierro, cobre y manganeso tienen un origen natural, como se demostró usando el modelo de los factores de enriquecimiento. Los valores indican que para estos elementos, mayoritariamente presentes en el aerosol < 45 μm, alrededor del 83% de la concentración de cobre, del 55% de la concentración de hierro y del 31 % de la concentración de manganeso, se encuentran en el aerosol entre 15 y 45 μm, aerosol sin potencial tóxico,

- los valores para plomo y cadmio son prácticamente iguales, en las fracciones de 45 μm y de 3 μm, lo cual orienta claramente hacia fuentes antropogénicas para ellos; además, se evidencia la potencial toxicidad del plomo,

- los valores para cadmio se encuentran muy por debajo de la norma establecida en el extranjero, y

- el plomo está sin duda concentrado en el aerosol < 3 μm; la ligera discrepancia entre los valores informados para < 3 μm y para < 45 μm, está dentro del margen de error que implica trabajar con dos tipos de muestreadores completamente diferentes, incluso en sus principios de funcionamiento (filtración: < 45 μm; impactación: < 3 μm). Además, los valores se encuentran muy próximos del valor de la norma antes señalada para el aerosol < 45 μm, destacando que los valores indicados corresponden a promedios anuales.

Los promedios anuales, constituyen una forma muy gruesa de observar la presencia de un elemento en el aire. Es mucho más adecuado hacer un análisis que incluya la evolución mensual, semanal y diaria de las concentraciones. Como ejemplo de la evolución mensual del plomo, en la **Figura 4** se muestran los resultados obtenidos en el área céntrica de la ciudad, entre 1978 y 1980 (**Préndez et al., 1993b**).

Se ve que las concentraciones aumentan notablemente durante los meses de otoño-invierno, alcanzando niveles verdaderamente peligrosos. Resultados similares para el aumento de las concentraciones durante los meses de otoño e invierno, se han observado también para cobre y níquel (**Préndez y Ortiz, 1982**).

La variación de las concentraciones a lo largo del día es otra información que ayuda a establecer las fuentes de origen del elemento. La **Figura 5** muestra dichas variaciones para diferentes metales pesados (**Ortiz et al., 1982**). La observación principal es la evidencia en el aumento de las concentraciones durante el día, lo cual relaciona la presencia de los elementos en el aire a la actividad de la ciudad y en consecuencia, a acciones antropogénicas, aún cuando su origen pueda ser natural, como es el caso de cobre y manganeso. Concretamente, ésto se vincula al levantamiento del suelo por la actividad humana. En el caso del plomo, la variación se relaciona a lo largo del día con el mayor tráfico vehicular.

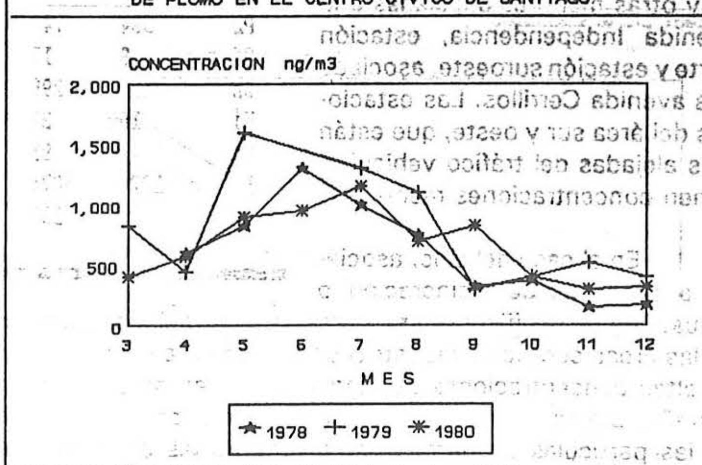
Otro aspec-

Cuadro 5. Concentraciones promedio de metales pesados (ng m^{-3}) en aerosoles atmosféricos de diferentes tamaños, en Santiago de Chile

Elemento	< 3µm	<15µm	<45µm
Pb	1245	*[1]	1211
Cd	11	*	10
V	ND[2]	21	ND
Hg	ND	*	6
Mn	90	68	115
Zn	596	303	1105
Cu	63	61	370
Fe	1468	2254	4102
Cr	ND	50	75
Ni	33	80	35
Ti	ND	*	276

[1] * Técnica analítica no apropiada
[2] ND: Concentración no determinada
Valores promediados a lo largo de los años:
- 1976-1983 para polvo <45µm (Préndez et al.)
- 1987-1993 para polvo <15µm (Morales et al.)
- 1983, para polvo ≤ 3µm (Préndez et al.)

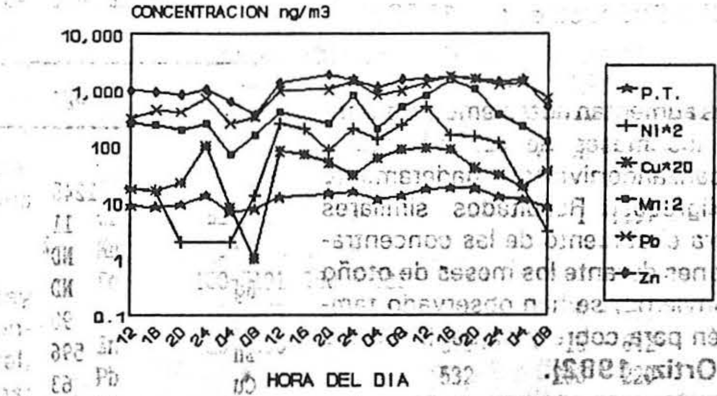
FIGURA 4. CONCENTRACIONES PROMEDIO MENSUALES DE PLOMO EN EL CENTRO CIVICO DE SANTIAGO.



ENTRE LOS AÑOS 1978 Y 1980 (PRENDEZ et al., 1993) to importante de destacar dentro de la ciudad, se refiere a la diferencia en las concentraciones de ciertos elementos, en distintas zonas de Santiago. El Cuadro 6 muestra de forma integrada por áreas, los resultados correspondientes a valores determinados en los mismos sitios de la Red de Vigilancia del Servicio de Salud Metropolitano del Ambiente, pero de manera independiente y con instrumental propio, para muestreos efectuados durante 1983 (Fuentes, 1986; Del Carpio, 1988).

FIGURA 5. CONCENTRACIONES DE Pb, Zn, Mn, Cu Y NI, EN AEROSOLES ATMOSFERICOS DE SANTIAGO

ORTIZ et al., 1982



A LO LARGO DEL DIA (P.T.= polvo total, en ug/m3)

Las diferencias están ligadas a las emisiones de fuentes específicas. La situación es particularmente clara para el plomo, elemento para el cual se postula usualmente a nivel urbano un origen vehicular, específicamente, la quema de gasolina plomada. El **Cuadro 6** muestra las concentraciones más altas en el centro cívico y otras menores asociadas a la avenida Independencia, estación norte y estación suroeste, asociada a la avenida Cerrillos. Las estaciones del área sur y oeste, que están más alejadas del tráfico vehicular, tienen concentraciones menores.

Cuadro 6. Concentraciones promedio diarias de metales pesados (µg m^{-3}), en aerosoles < 3 µm, colectados en diferentes lugares del Área Metropolitana

Elem.	Sur	Norte	Centro Cívico	Sur Oeste	Oeste
Pb	384	744	1245	843	272
Cd	8	17	11	10	16
Zn	128	295	596	665	86
Ni	16	23	33	25	21
Cu	44	91	63	45	35
Fe	1224	3074	1468	1295	2437
Mn	52	132	90	82	108

En el caso del cinc, asociado a procesos de incineración o industriales específicos, las mayores concentraciones están coherentemente ubicadas en las áreas céntrica e industrial de la ciudad, a la época del muestreo. La presencia de altas concentraciones de hierro en el área norte, puede resultar a primera vista extraña. Sin embargo, la explicación surge cuando se postula que el hierro presente en las partículas de tierra existente sobre las calzadas o en las bermas de tierra descubierta de vegetación, muy frecuentes en esta área, es molido y resuspendido al aire, por efecto del tráfico vehicular. Esta situación es también aplicable a la zona oeste, la segunda en importancia en este sentido, en la cual adicionalmente existía a la época un elevado número de calles sin pavimentar, además de canchas de fútbol de tierra.

En el área norte, se han efectuado también determinaciones de metales pesados a alturas de 2 a 3 m de la superficie del suelo y a unos 300 m sobre la superficie. En el último caso, el monitor de partículas se ubicó sobre la capa límite atmosférica (CLA).

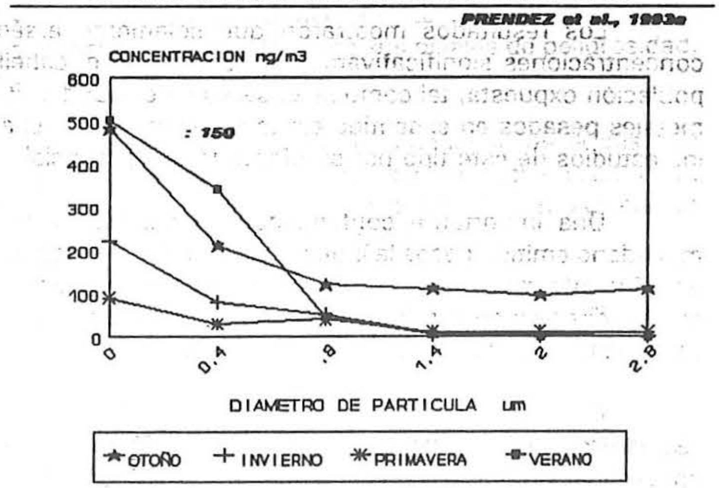
El Cuadro 7 muestra los resultados para tres metales pesados (Apablaza, 1991). Se observa que, para los elementos antropogénicos, generados desde su fuente con diámetros pequeños o en altura (plomo y cinc), las concentraciones son sensiblemente iguales sobre y bajo la capa de inversión térmica. En cambio, para hierro, elemento natural proveniente del suelo, las concentraciones disminuyen con la altura al ser inicialmente generado con mayores diámetros y posteriormente reciclado parcialmente al aire con diámetros menores, por acción antrópica.

Cuadro 7. Concentraciones promedio de metales pesados (ug m^{-3}) en aerosoles < 3 um, colectados a diferentes altitudes en el área norte de Santiago (valores calculados de Apablaza, 1991)

Elem.	En superficie	Sobre CLA
Pb	355	411
Zn	630	611
Fe	2860	1829

La asignación definitiva de la fuente de origen del plomo en el aire de Santiago, se hizo mediante el estudio detallado de la relación entre concentración y tamaño de partícula bajo los 3 μm. Para ello se consideran las concentraciones en 6 fracciones con diámetros crecientemente mas pequeños. Los resultados se grafican en la Figura 6 (Préndez et al., 1993b).

FIGURA 6. CONCENTRACION de Pb, EN AEROSOLES DE SANTIAGO, EN FUNCION DEL TAMAÑO DE PARTICULA Y EN DISTINTAS EPOCAS



Las curvas muestran que en cualquier época del año, las concentraciones aumentan en la medida que disminuye el diámetro de la partícula que lo contiene, siendo particularmente elevadas bajo 1 μm y en el período de otoño e invierno. La curva correspondiente al material particulado eliminado desde el tubo de escape de los automóviles que utilizan gasolina plomada, tiene exactamente la misma forma, pero con concentraciones que son 150 veces mayores.

Al tratarse de material muy fino, se dispersa rápidamente en la atmósfera en los primeros metros después de emitido, disminuyendo de esta forma su concentración local. Pero, por la misma razón, se dispersa homogéneamente y permanece largo tiempo suspendido en la atmósfera antes de adquirir suficiente peso como para ser redepositado por efecto de la gravedad. Dicho comportamiento puede explicar los resultados del **Cuadro 7**.

También se ha informado la presencia de arsénico en el aire de Santiago, con concentraciones de 5,3 ng m^{-3} en 1976 y de 27,3 en 1978 **(Huerta, 1980)**.

EFECTOS OBSERVADOS PROVOCADOS POR LOS METALES PESADOS

La contaminación producida por metales pesados emitidos y transportados a través del aire ha sido detectada sobre otros medios. A nivel internacional, hay numerosos estudios que afectan a los seres humanos y a otros seres vivos. A nivel nacional, la información es más escasa, aunque la literatura señala a lo menos estudios efectuados sobre seres humanos, sobre suelos y sobre ciertos alimentos.

En el primer caso, los trabajos se refieren a la eventual absorción en el cabello humano, de metales pesados emitidos al aire por una refinería de metales. La cuantificación, realizada mediante espectrofotometría de absorción atómica y análisis por activación neutrónica, incluye los siguientes elementos: arsénico, cobalto, cromo, cobre, hierro, mercurio, plomo, antimonio, selenio y cinc. Para el estudio se consideraron tres poblaciones diferentes de la región, una de las cuales directamente expuesta al aerosol emitido desde la refinería de Ventanas **(Cassorla et al., 1983; Aveggio et al., 1984)**.

Los resultados mostraron que solamente arsénico y bromo alcanzaban concentraciones significativamente mayores en el cabello de los habitantes de la población expuesta, tal como se observa en el **Cuadro 8**. Arsénico y bromo no son metales pesados en el sentido estricto; sin embargo, el arsénico se suele incluir en los estudios de este tipo por su efecto tóxico potencial.

Una importante contaminación de suelos y vegetales provocada por el molibdeno emitido desde la industria refinadora de metales Molimet (al sur de Santiago), fue informada hace algunos años **(Morales y Schalscha, 1984)**. El impacto estaba directamente relacionado con la distancia a la fuente emisora y resultaba particularmente peligroso para el ganado del área.

En el caso de los alimentos, dos grupos independientes de investigadores **(Guerrero, 1981; Díaz et al., 1983)** han utilizado la lechuga como indicador de contaminación. Este es un cultivo de alto consumo entre la población chilena, cuyas hojas quedan en contacto directo con el aerosol atmosférico.

Las muestras, tomadas en distintas zonas cercanas a la ruta 5-Norte del Área Metropolitana, en las comunas de Renca y Quilicura, mostraron un alto contenido de plomo, variando entre 2,5 y 6 ppm, lo que supera notablemente lo establecido por el reglamento sanitario de los alimentos, el cual indica un valor máximo de 2 ppm de plomo. La OMS recomienda sólo 0,4 ppm.

Cuadro 8. Concentración promedio y rangos de As y Br (mg kg^{-1}), para muestras de cabello humano de poblaciones próximas a la fundición de cobre de Ventanas (Cassorla et al, 1983)

	POBLACION		
Elem.	Expuesta	Rural	Urbana
As	1,46	0,28	0,36
	(29- 5,48)	(0,037-1,3)	(0,065- 1,19)
Br	6,7	2,15	2,29
	(0,24-44,3)	(0,086-5,3)	(0,153-25,7)

CONCLUSIONES

De acuerdo a la información entregada en el presente trabajo, las principales conclusiones alcanzadas son:

- en la Región Metropolitana, no existe suficiente información respecto de la presencia en el aire de elementos pesados de gran importancia por su eventual toxicidad, tales como vanadio, arsénico, antimonio y mercurio,

- existe insuficiente información respecto de la presencia de metales pesados en el aire de otras ciudades del país, que no sea Santiago,

- la información respecto de los efectos producidos por metales pesados en el aire de las áreas urbanas chilenas, es escasa y requiere ser incrementada, debido a su potencial de toxicidad para la salud de la población,

- es de la mayor importancia establecer normas primarias y secundarias para metales pesados en el aire, a fin de establecer adecuadamente sus niveles de peligrosidad, tanto para la salud humana como para la del ambiente,

- en Santiago, el origen del plomo se encuentra en la combustión de la gasolina plomada, usada por algunos vehículos motorizados; sus concentraciones en el aire se encuentran en niveles peligrosos para la salud de la población, en especial en el área céntrica, de acuerdo con la normativa extranjera, y

- la cuantificación de los metales pesados en el aire y la aplicación de adecuados modelos, permite determinar la peligrosidad o inocuidad de las emisiones de sus fuentes específicas. Con ello se logra un gran avance en la evaluación cuantitativa del impacto real que pueden tener ciertas fuentes emisoras puntuales (fijas o móviles) sobre el ambiente. Como consecuencia, se facilitan los procesos que implican la eliminación de los contaminantes al ambiente.

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CHAPTER 16

THE NEUROTOXICITY OF LEAD

INTRODUCTION

Most of the heavy elements have neurotoxic effects, either on the peripheral nervous system (PNS), or on the central nervous system (CNS). A brief list of the neurotoxic effects of the heavy elements is given in Table 16.1. The neurotoxicity of mercury and arsenic is not disputed, and there is no doubt that lead has neurotoxic effects on both children and adults when the dose is high. A lot of effort has been put in to investigating whether or not low level lead exposure impairs the neuropsychological functioning of children [28,65,79,100]. The weight of evidence does point to some effect on intelligence, cognitive functioning and behaviour. It is necessary in such an investigation to have sensitive and reliable measures of both lead levels and neuropsychological functioning, as well as statistical techniques to handle the data, and reliable estimates of confounding variables. Though lead is not as dangerous as mercury on a mass basis, there are other reasons why lead is more dangerous as a general population toxin. These are, its greater production, and its wide use in areas where people come into contact with it, especially lead solder, painted houses and lead additives in petrol. A comparison of some of these features for the four most common toxic heavy elements, are listed in Table 16.2.

ESTIMATES OF THE BODY LEAD BURDEN

The body lead burden can be estimated by measurement either of the lead content in materials such as lead in blood, teeth, hair, urine, fæces and bone, or the biochemical effect of lead, such as its effect on the haemopoeitic system.

Lead in Blood

The most common measure of lead is lead in blood, it is mainly estimated in the whole blood, but also in the plasma or in the red blood cells. Blood is difficult

TABLE 16.1 Neurotoxicity of the Heavy Elements

Element	Neurotoxic effects
Mercury	CNS: brain damage, visual, sensory, auditory and coordination dysfunction, PNS: e.g. tremors
Cadmium	Nothing reported
Lead	CNS: encephalitis, behaviour, inattention, IQ deficits PNS: reduced nerve conduction
Indium	PNS: paralysis of limbs, convulsive movements
Thallium	CNS: encephalitis, brain tumour, PNS: polyneuritis
Arsenic	CNS: vertigo, restless, irritability, hearing loss, PNS: motor paralysis, peripheral neuritis
Antimony	?
Bismuth	PNS: peripheral neuritis
Selenium	CNS: depression, irritability
Tellurium	PNS: tremors, diminished reflexes, convulsions

to sample accurately and reliably, and is sampled either as venous blood or capillary blood. Both methods are subject to contamination, but the problem is more significant in the capillary method as a small volume of blood is taken. However, with rigorous methodology capillary sampling should be satisfactory for small samples [43], and provided high results are checked with venous sampling.

A single PbB measurement is not adequate as a persons blood lead can fluctuate over time [36,38], and it represents recent exposure [33,75,77,100, 105,115]. A person could easily be incorrectly classified if a high lead exposure had occurred a long time before the blood was taken. Blood lead results typically have a variability of ±10 to ±15%.

Lead in Teeth

After blood, children's deciduous teeth have been the next most often used tissue for estimating body lead. The distinct advantage of teeth is that they provide a record of past lead exposure [5,19,29,36,42,77,90,106,109,126], therefore there is less of a chance of incorrectly classifying people in terms of their overall lead exposure [33,86,100,118]. Moderate association has been found between PbB and tooth lead (e.g. r = 0.47, p<0.001) [5,118,127], however, as the two materials reflect different temporal lead exposures, it is not necessary that they show a close correlation. We have discussed previously the problem of tooth analysis and the different matrices and type of teeth in Chapters 4 and 13. If agreement could be reached on what tooth material and tooth type to sample, it is likely that teeth would be the best tissue to use in epidemiological studies of the health effects of lead.

TABLE 16.2 Relative Toxicity and Availability of Mercury, Cadmium, Lead and Arsenic to Human Beings

Element	Crustal conc. µg g^{-1}	Production × 1000 t (1985)	Toxicity	Tolerable intake µg d^{-1}
Lead	13	4100	mod. to highly	430
Mercury	0.08	6	extremely	~40
Cadmium	0.2	14	highly	~60
Arsenic	1.8	50	highly	~60?

Lead in Hair

An accessible tissue for the measurement of lead is human scalp hair, which has been used in the study of neuropsychological effects of the metal [43,97,98,121]. As discussed in Chapter 13 hair presents more problems than teeth because of the endogenous and exogenous sources of lead in the fibre. The best hair sample is that taken close to the scalp, reflecting more closely internal lead levels. The best position to sample is probably the nape of the neck. Hair roots may be even better material to sample.

Lead in Other Materials

Other materials such as urine and fæces have not been widely used as a measure of the body lead burden [5,14,20,43,49,119,120]. Lead released from the body in urine and fæces by chelating agents, such as penicillamine and EDTA may be used to measure the body lead burden [14].

As outlined previously lead interferes with the biosynthesis of haem at a number of steps. Therefore various species and abnormal products accumulate, providing possible markers for the body lead burden [19]. The markers most frequently studied are, EP, the activity of δ-ALAD in blood and levels of ALA and CP in urine. Little use has been made of these methods.

NEUROPSYCHOLOGICAL METHODS

Cognitive and Behaviour Testing

A variety of neuropsychological measures are available which aim to measure functions such as: IQ (full scale, performance and verbal) fine and perceptual motor skills, verbal processes, visual perception processes, gross motor activity, behaviour ratings and nerve conduction. An area of difficulty is, finding tests sensitive enough to detect small changes in neuropsychological functioning [19,24,33,36,40,41,45,77,82,84,86,87,91,100,104,105,108,109,111]. The Wechsler Pre-school and Primary Scale of Intelligence, WPPSI, test which measures perceptual motor ability revealed significant differences between groups with PbB levels above and below 29-39 µg dl^{-1}, whereas the Denver Development Screening Test, DDST, test which measures language and fine motive adaptive ability revealed differences between groups with PbB levels above and below 39-60 mg dl⁻¹ [91]. Therefore it is necessary to consider a combination of tests, perhaps a mixture of a standardized IQ test (e.g. Wechsler Intelligence Scale for Children - Revised, WISC-R) and specialized neuropsychological tests [108]. Measures in more than one setting may help distinguish between pervasive and situational effects [109]. Testing must be objective and blind with respect to the lead measure [19], and bias may be introduced by using more than one tester.

Increasing the battery of tests does not necessarily improve the results. At a 5% level of significance one test in 20 will show a significant effect by chance [34,86,108,109,111]. It is difficult to obtain objective parent and teacher ratings of child behaviour, and care is necessary in producing a questionnaire, and in the method of presentation to parents [72,126].

Confounding Variables

Confounding variables (CV's) are factors which associate with the outcome of interest, i.e. the neuropsychological function, or the lead exposure or with both together [19]. Where appropriate these variables have to be considered, and a list is given in Table 16.3. Two methods are available to handle CV's, either matching exposed and control groups for the variables, which is difficult to do adequately, or controlling for the variables statistically [19,33,100,105]. In longitudinal studies (i.e. carried out over time) of the same sample, it is reasonable to expect most CV's to remain constant [37].

TABLE 16.3 Confounding Variables

Socioeconomic status (SES)	Birth and medical factors
Parental: IQ	Pre-natal problems
Education level	Birth weight
Attitude to child	Birth order
Attitude to school	Number of pregnancies
Interest	Mother's age at birth of child
Restrictiveness	Mother's exposure to toxins
Father head of house	Mother's mental health
Father's occupation	Infections
Mother's occupation	Iron balance
Family income	Trauma
Care-giving environment	Medical problems
Nourishment	Pica
Social class	Genetic factors
Social disadvantage	Host sensitivity
Marital relationship	
Environmental factors	**Physical factors**
Type of residence	Age
Length of time in residence	Sex
Geographic location	Race
Home cleanliness	Number of siblings
Smoking habits	
Alcohol use	

Extensive criticism of various studies centres around the attention, or the inattention, given to CV's [36,37,71,82,84,87,111]. The socio-economic status (SES) of the subjects is relevant, but is difficult to measure quantitatively. Social class, or father's occupation, or income have been used, but they are rather crude measures. Both, under-estimates and over-estimates of SES, can influence the final assessment of the effect of lead. Many of the factors listed in Table 16.3 are inter-dependent and if too many of these are used in an analysis this could conceal the influence of other factors [1108,110].

The biological variability of people is also a factor, to which little attention has been given [24]. Some people are sensitive to a certain level of a toxin, while others are not.

Statistical Methods

The lead concentrations and neuropsychological data obtained have to be handled by statistical techniques, in particular multivariate analysis. The ability to discriminate between various inter-active factors depends on the sample size [18,19,40,41,82,100, 109,111]. The sample size required is determined by, the level of significance desired, how small a difference one wishes to detect, and the frequency of the factor in the population [19]. To increase the certainty, and decrease the detectable difference, requires an increase in sample size. Samples too small tend to give inconclusive results.

The selection of exposed and control groups has to be random, but for a number of reasons some subjects will be eliminated from a study This may produce a sample bias which needs to be tested. When the sampling has been selective or stratified, care is necessary over generalizing the results [19].

Confounding variables may be determined by forward selection, where the experimenter makes the choice, or by backward selection, where a CV is eliminated statistically because its inclusion or exclusion does not change the lead exposure regression coefficient. This can mean that a CV may be required for one outcome measure, but not for another [37].

Outliers in the data need to be determined statistically and removed before further processing of the data [37]. In a material, such as teeth, because of the natural variability in the lead level an outlier may in fact be a real value and must be included [42]. Some statistical packages have constraints over the number of covariates that can be handled, and this could be artificially restrictive [37]. The statistical limit to the number of outcome measures (per subject) that are required to demonstrate group, as distinct from individual, differences is one third the sample size [13].

EPIDEMIOLOGICAL STUDIES

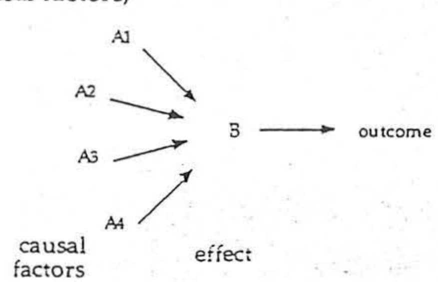
The steps in epidemiological studies include, determination of the sample size, sampling, measurement of the lead exposure and the outcome factors (i.e. neuropsychological functioning), deciding on confounding variables and statistical handling of the results. Epidemiological studies can be either retrospective or prospective. In a retrospective study people with a particular outcome (limited to one) are compared with a control group regarding their lead exposure. It is difficult, and may be impossible, to fully control for the CV's. In a prospective study, which is a better approach, groups with different lead exposure are studied over a range of outcome measures [7,16,23,24,33,37, 54,100,105]. For longitudinal prospective studies, lead exposure and outcome measures are estimated over time, and the CV's could well remain relatively constant and are less of a problem. An ideal study would start with pregnant women and then follow their children over a number of years.

Cause and Effect

It does not automatically follow that if a strong association exists between two factors that the relationship is causal [22,37,63,100,109,122]. Nevertheless, a strong association cannot be ignored. Requirements to establish a cause and effect relationship are: a consistent trend over a number of studies, a dose-response relationship, the effect is biologically plausible, that other traumata can be excluded or shown to not rule out the cause under consideration, the association is strong and specific, that the cause precedes the effect in time, that the evidence is coherent i.e. consistent with the natural history of the outcome and disease, and experimental evidence is available such as a study of accidental exposure [19,108]. A strict adherence to all these requirements could well rule out any cause and effect relationship being discovered. Eventually it is the trend in the available evidence, and the quality of the epidemiological study that are important in the decision.

Some evidence obtained does not distinguish clearly between either lead being the cause of the outcome or the outcome predisposing people to high lead exposure [37,109]. In such cases other information is required about the situation in order for one conclusion to be favoured over another [37].

Two models of cause and effect have been proposed [19]; (a) multiple independent causal factors,

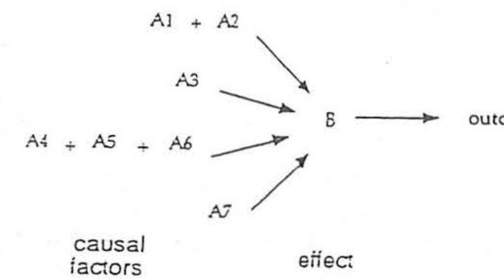


and (b) cumulative and sometimes independent causal factors

$$A1 + A2 + A3 + A4 \rightarrow B \rightarrow \text{Outcome}$$

causal factors effect

The second model is often used in analysis of results, but a more complex situation may well exist, i.e. a mixture of models (a) and (b),



NEUROPSYCHOLOGICAL STUDIES

The various neuropsychological studies on lead can be classified in different ways, such as the degree of lead exposure, or in terms of the subject, either an adult or child, or the type of epidemiological study, i.e. prospective or retrospective, cross sectional or longitudinal. A method of classification used by Rutter [108-111] will be followed here. The classification is: (1) studies of children with mental retardation or behavioural deviance; (2) studies on the effect of reducing the body lead burden by chelation; (3) studies of people living close to smelters; (4) studies of small groups of people in a clinical environment and (5) studies of large populations selected in a random manner. Clearly the groups merge into each other, especially groups 3, 4 and 5.

Mental Retardation Studies

Studies of mental retardation in relation to lead are retrospective, in that an outcome has been determined and people with or without the outcome are compared as regards their lead exposure. The principal limitation, is the restriction in the number of neuropsychological outcomes. The sample is normally stratified and is generally small in size.

Outcomes that have been selected are; mental retardation [9,32,74,76], learning disability [97,98] and autism [16,17]. Studies in Glasgow [9,76] demonstrate good correlations between mental retardation, blood lead levels and water lead levels. The quality of the matching of the mentally retarded and control children, and the handling of CV's may be criticized, but even so for water lead levels >800 mg l^{-1} the chance of mental retardation increases by a factor of 1.7. In a Welsh study [32], no relationship between water lead levels and mental ability was observed, but in this case, the water lead levels were

<300 mg l^{-1}. Autistic children with a high incidence of pica were found to have elevated blood lead levels [17], but the significant relationship disappeared in a second study, though the trend persisted [16].

In other studies, children diagnosed with mental retardation and/or hyperactivity [20,21,23,24,129] have been grouped according to; those with a probable cause, those with a possible cause and those with an unknown cause. The groups were then compared according to their lead exposure, and in some cases [21,24], the blood lead levels were higher in the children with no known cause of their illness. Some criticisms directed at this work include; possible sample bias, little or no consideration given to pica and SES, poor matching of groups, small samples, over diagnosing probable cause and unknown cause, and no clear source of lead [15,45,82,109]. Even so, a distinct difference in the PbB levels between the groups with probable and unknown aetiologies existed. Whether or not a causal relationship occurs is less certain.

Chelation Studies

In principle the investigation of the neuropsychology of children with a high lead burden before and after chelation is a powerful method to demonstrate a causal relationship [109]. Hyperactive children, of no-known or minimal cause, or with a history of lead poisoning were treated with either penicillamine, which removes lead from the system, or with methylphenidate, which helps in hyperactivity, or with a placebo. Improvement in teaching ratings, parent ratings and global impressions occurred for children on both drugs, but no change was apparent for those who received the placebos, however, more dropouts occurred from the study for the placebo group. The children receiving penicillamine also had their blood lead levels reduced [25]. Though the quality of the sample has been questioned the results do point to a possible causal relationship, especially because of the use of contrasting interventions [108].

Smelter Studies

Studies of people living near or working in lead based industries, have one advantage, namely, the source of lead is clearly definable. A number of studies have been carried out on children and adults [2,4,7,28,44,46,47,48,52,58,59,60-64,69,70,73,95,104,114,115,116,123,130]. Most have used blood lead as the measure of lead exposure, and frequently only one measurement was made. Two PbB measurements at different times provides the basis for a better classification of the high and low lead groups. An Australian study addressed this problem, and a number of blood lead measurements have been taken at different times during the study [4,28].

A problem for smelter studies is obtaining a big enough sample, and maintaining it throughout the study. Another problem is determining the 'best time' to carry out the neuropsychological testing of outcome measures in relation to the lead measure. Finding matched pairs, increases difficulties and

often the sample size can be drastically reduced because of this. Often age, sex and race have been matched, and estimates of SES have varied from, not considered to the use of the father's occupation and income.

In a large (592 children at 2 years old) prospective epidemiological study at Port Pirie, Australia [4,28], the children's lead exposure was tracked from the 16th. week of pregnancy. The increase in blood lead levels in the sample (especially for post-natal blood) was associated with a significantly reduced Bayley Mental Development Index (MDI) score. The MDI score drops ~2 units for every 10 µg dl^{-1} lead in the blood. It is planned to carry the study on to age 7 years, and preliminary results at age 4, using the McCarthy scale of children's ability, also shows a significant negative association to blood lead. It was also noticed that preterm births are more likely when the blood lead level of the mother was elevated [4,28]. A similar result has been found in Glasgow [28].

A summary of some of the studies on children is given in Table 16.4. Summaries have disadvantages as much of the data has to be omitted, and it gives the impression that the studies are all of equal quality. A number of the investigations find a lead effect [4,57,59,60,130], whereas others find no effect [52,70,104]. The weight of evidence is suggestive that elevated blood lead levels are associated with some impairment of IQ and neurologic functioning. It is likely that a spectrum of effects occur [63], and what is observed depends on the cut-off point between the high and low lead groups, as well as the sensitivity of the neuropsychological tests. A cut-off point of 35-40 µg dl^{-1} could be too high, so that the two groups differ little in their neuropsychologic effects. The Australian study indicates a lead effect where the blood lead levels are much less, around 11-20 µg dl^{-1} [4,28].

Clinic-Type Studies

A number of clinic-type studies have been carried out, mostly in the U.S.A. The studies are generally prospective and cross-sectional. Frequently the the cut-off blood lead level is >30 mg dl^{-1} for the lead group and <30 mg dl^{-1} for the controls, which, as for the smelter studies, may be too high. However, at the time when many of the studies were carried out, a PbB level of 30 mg dl^{-1} was not considered too high. Teeth and hair have also been used as lead indicators.

The principal outcome measure used in the studies is mental ability as measured by IQ tests. Electroencephalographic (EEG) measurements have also been used. The CV's mostly considered were age, sex, race and SES. Parental IQ and/or education have been considered as important variables.

A majority of the studies (including the EEG studies) demonstrate a significant lead effect, and in some a small negative trend was observed, but not statistically significant. Comparative data, and the findings of the various investigations, are listed in Table 16.5. The results from studies which have not taken into account CV's must be considered with caution. A longitudinal study [30,31], with some methodological errors, indicated that over a 3-4 year period the damage initially observed was still obvious. Unfortunately, the blood lead

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TABLE 16.4 Summary of Studies on Smelter Children

Location	Sample size	Blood lead $\mu g\ dl^{-1}$	Neuropsychol. tests	Authors' findings	Comments	Reference
U.K.						
London	215	Mean 33.1	IQ, behaviour	No effect	A weak PbB/distance correl., one PbB, SES not handled well.	2,64
Birmingham	851 1642	Near factory unpolluted areas	11+ Exam	No effect, closest to factory did slightly less well	No measure of lead exposure, matched somewhat for age, SES, birthrank, maternal age.	52
Manchester	24 23	>35 ≤35	Behaviour, general development	No effect, high lead did slightly less well	Matched for age, sex, SES, parent educ. area, length of residence; age & school accounted for most variation; 3 yr study.	104
London	34 48 49 35	7-10 11-12 13-16 17-32	IQ, educational attainment, teacher ratings	An effect for IQ and dose/response	Controlled for SES, sex, age; tested 9-12 months after one PbB measure; decided SES measure too crude.	130,63
U.S.A.						
El Paso	50 & 46 81 & 78	≥40 <40	IQ, behaviour neurologic tests	An effect (IQ (perform.) finger wrist tapping)	Some matching, age, sex, SES, language, time of residence.	123 62
	138 controls	mean 50 mean 20	IQ, teacher reports, neurologic tests	No effect	Some matching, age, sex, race, income; children away from area during investigation.	70,69
Shoshone (Idaho)	202	≥40, <40	Nerve conduction velocity (NCV)	An effect	Concentric sampling, matched, age, sex, SES, time of residence.	58,59,60
	34 + 20 matched pairs	>40, <40	IQ	No effect	Matched, sex, age, SES, length of residence, type of residence; variation between testers >samples.	47
	50 matched pairs	≥40, <40	IQ	An effect		
	168		IQ	An effect		

Table 16.4 continued

Location	Sample size	Blood lead $\mu g\ dl^{-1}$	Neuropsychol. tests	Authors' findings	Comments	Reference
Shoshone (Idaho)	50 matched pairs 6 with low NCV	≥40, <40	NCV	No effect	NCV on Gregory's group and 6 with low NCV in Landrigan's study	44
Belgium	42 (<1 km) 36 (2.5 km) 73 controls	27.9 16.0 11.5	EEG	No effect	Controls matched for age and SES	35
Australia (Pt. Pirie)	592	9.4 (mothers) at 16 months 10.4 (mothers) at birth	Bayley, MDI, PDI	An effect	Corrects for counfounding vcariables e.g. caretaking environment	4

TABLE 16.5 Summary of Clinic-type Studies of Children

Study	Sample	Blood lead $\mu g\ dl^{-1}$	Tests	Results	Comments
Boston (USA) (1972,1974) [102,103]	58 42 (1.5 yrs later)	>40 >35	IQ, neurologic	IQ 8 pt increase after 1.5 yr	Longitudinal study, no CV considered.
Boston (USA) (1973) [39]	24 22	>40 controls	NCV	A lead effect	No CV considered.
New york (1974) [1]	Variety	40-80	IQ, behaviour	IQ 22 pt difference low PbB & tooth lead and tooth lead poisoned	No CV considered.
New York (1972,1977) [55,56]	24, 25 31, 36	81, 38 80, 28	Neurologic, social, language	No effect	Matched; age, sex, race, SES, pica and neonatal environ . Cut-off PbB level high.
Virginia (USA) (1972, 1975) [30,31]	70, 72 67, 70 (restudy 3-4 yrs later)	58, - 202, 117 $\mu g\ g^{-1}$ tooth lead	IQ, neurologic, behaviour	1972 5 IQ, 1975 3 IQ points difference	Matched; race, sex, SES, housing density, no. children <6 yrs,pica in lead groups. Results suggest permanent damage, Longitudinal study.
New York (1974,1976,1981) [36,96,128]	30, 50 32, 31 27, 73	40-70, 10-30 27-49, ≤26 ≥38, <37	IQ, teacher ratings, behaviour	1981 12 IQ point difference	Controlled for age, sex, parental IQ and educ., birth wt., SES positive effect in both studies, but dismissed by authors (1981) due to inadequate control of SES.
Cleveland (1985,86) [28]	132 Mother/infant pairs	6.5 mothers 5.8 cord	Behaviour	Some effect	Three out of 17 outcomes associate with maternal or cord blood lead.
Cincinnati, (1975) [6]	27 matched pairs	>50, <30	IQ, neurologic, behaviour	IQ -1 to 2 points difference	Matched; age, sex, race, SES; parent and teacher assessments weak.
Rhode Is (1974, 1979) [107]	45 45	≥40 <40	IQ, neurologic behaviour	IQ 16 points between controls & lead poisoned and 5 points controls & long exposed.	Matched; sex, age, race, SES; appears to show a dose/response relationship.

Table 16.5 continued

Study	Sample	Blood lead $\mu g\ dl^{-1}$	Tests	Results	Comments
Boston (USA) (1977) [88]	41 35	>50 <30	IQ, neurologic	Weak positive effect	Matched SES, birth weight; big time gap between PbB and outcome measures.
New York (1978,1979) [26,27]	579	5-44	Behaviour, teacher ratings, academic achievement	Positive result	Controlled for age, sex, culture group; SES assumed same for all sample.
Nth Carolina (1980,81) [72]	40 43	≥31 <31	Behaviour, neurologic	No effect	Matched; sex, age, race, SES; well conducted, hyperactivity in home environment, no school.
Chicago (USA) (1981) [112]	Variety	<40 to >200	IQ, neurologic, NCV, EEG.	Negligible effect IQ 4 pts difference <40 to >200 $mg\ dl^{-1}$	No control of CV, except case of siblings.
Maryland (1981) [121]	149	Hair lead	IQ, neurologic	Approx. 30 IQ pts over entire range	Controlled for sex, race, SES, urbanicity. Used hair lead, could have sample bias. Cd also has an association
Sydney (Aust.) (1982) [68]	72-108 72-108	>19 <9	IQ, neurologic, behaviour	No clear difference	Handles CV by correlation, controlled for age, sex.
Boston (USA) (1980,1981) [13,89]	19 22	Dentine lead	Psychol. measures EEG	Positive effect	Combined EEG and psychological testing and obtained improved explanation of variance.
Nth Carolina (USA) (1981,1983) [11,92,93]	69 100 (63 studied) 28 (reasses)	6-59 7-59 14-39	EEG IQ, EEG EEG	All give a positive effect for lead	Results suggest effect occur at PbB <15 $mg\ dl^{-1}$.

levels of the controls were not measured. The SES factor was carefully considered, making use of parent education, occupation and family income.

Some studies [36,96,128] have aroused a lot of comment, probably because the authors reversed the conclusions of their earlier study. Initially a positive effect was found to exist between a lead group with PbB of 40-70 μg dl⁻¹ and controls 10-30 μg dl⁻¹ [96]. A restudy of the same group [36], five years later, demonstrated only a small positive effect which was not statistically significant. The authors' suggested there were methodological problems in the first study. In a third prospective study 132 mother/infant pairs were studied using maternal blood at the time of delivery and cord blood lead levels for estimating the lead exposure. Significant relationships were found between the cord blood lead and abnormal reflexes and neurological soft signs, and also between maternal blood lead and muscle tonus [28].

The four EEG studies [11,13,89,92,93] all showed an effect with increasing PbB levels. Also an effect was discernible at PbB levels <15 μg dl⁻¹, though no threshold was apparent over the PbB range 7-59 μg dl⁻¹. The combined use of EEG and psychological measures [13,89] appears to be a more powerful predictor of PbB values and neuropsychological impairment than the two separate measures.

The results for most of the clinic-type studies are weighted towards a neuropsychological effect of lead. Issues, such as the danger level of PbB, and satisfactory cut-off levels for study, are not resolved.

Population Studies

Provided the sample in a population study is representative, the findings may be extrapolated to the general population. Hence there is a lot of interest in this type of epidemiological study. Over recent years a number of studies have been conducted [28,40,41,43,51,66,77,89,91,100,101,113,117,118,126,127].

There are difficult areas in general population studies. Locating the source of lead can be difficult. The sample needs to be representative, but in the end the experimenter is dependent on the cooperation of the participants. A range of confounding variables can be expected, making it necessary to take care over establishing and controlling for these factors. Finally, it is best to find a measure of lead which is more than one single measurement. A summary of some of the studies is given in Table 16.6. Many of the studies involve a great deal of work involving a number of disciplines.

Studies in the USA The investigation that created interest in population studies and has evoked most comment and criticism, was published in 1979 by Needleman's group [77]. From a population of 3329 eligible children two groups, one of 100 children with dentine lead <6 μg g⁻¹ and one of 58 children with dentine lead >24 μg g⁻¹ were selected. The two groups were then tested with a number of neuropsychological tests and the results statistically analysed, controlling for mother's age at time of subject's birth, mother's educational level, father's SES, number of pregnancies and parental IQ. The IQ's found for the low and high lead groups were: full scale 106.6, 102.1; verbal 103.9, 99.3; and the performance 108.7, 104.9, i.e. a difference in the region of 4-5 points. Also ten of eleven teacher behaviour ratings were significantly different between the two lead groups. In addition 2146 children were given teacher behaviour ratings and the results considered in terms of six dentine lead groups. The high lead groups performed less well on nine of the eleven behaviour ratings.

Numerous criticisms of the study include; the use of dentine lead as a lead marker, omission of the source of lead, sample selection, handling of the confounding variables, the large number (66) of neuropsychologic outcomes tested, the testing technique, the statistical treatment of the data, and the methods of obtaining the teacher ratings [3,8,35,36,37,45,67,70,100,106,122]. The work has also had favourably criticism, such as the planning, good reasons for excluding certain people and a sound choice of psychological tests [3,99,106,109]. Needleman and coworkers have responded to most of the above points [78,80,83-86] and despite the criticisms the study does demonstrate an effect of lead on neuropsychological functioning of children.

The data from the study has been analysed in other ways [10], which indicates that lead disrupts the child/maternal IQ relationship. For the low lead group maternal IQ accounted for 24.7% of the child's IQ variance and the addition of lead did not alter the value, whereas for the high lead group, maternal IQ accounted for 16.1% of the variance, which rose to 27.1% when lead was included.

Two further studies [86,89] have replicated the teacher behaviour rating study on a group of 1273 children. A group of the children studied in the 1979 report were re-studied 4 years later [86] with respect to behaviour in school. Some of the tests indicated a dose-response relationship.

A 4-7 point deficit on the Bayley MDI scale was observed for 216 children at age 6 months, grouped into high, medium and low lead exposures based on maternal cord blood lead levels. The lower score occurred for the higher lead group [28]. The deficit persisted when tested at ages 12, 18 and 24 months. The primary source of lead was identified as coming from the mother during pregnancy.

A study of 242 mothers and 280 infants in Cincinnati [28] found that the prenatal blood lead (mothers) showed a significant negative relationship with MDI and PDI (Bayley Psychological Motor Development Index), but not with the child's post natal blood lead levels.

A group of 218 children in Chicago were divided into three lead groups based on their blood lead levels [91]. A number of blood lead measurements were carried out on each child over 3 years. A significant difference was found between the high and low lead groups in verbal productivity, perceptual and visual motor functioning, however no control of CV's was attempted, except that the sample was said to be homogeneous.

TABLE 16.6 Summary of Population Studies of Children

Study	Lead Measure	Sample	Tests	Confounding variables	Results
Boston (1979) [77]	Dentine	3329 teeth from 2335 a)high lead >24 $\mu g\ g^{-1}$ 100 low lead <6 mg g^{-1} 58 b)Six groups, <5.1, 5.1-8.1, 8.2-11.8, 11.9-17.1, 17.2-27.0, >27.0 $\mu g\ g^{-1}$ 2146 children	WISC-R Seashore rhythm Token Sentence repetition, reaction time Eleven teacher behaviour ratings	Family size, mother's age at time of birth, mother's educ., SES parental IQ None on whole sample, same as above on high and low lead grups	Significant differences between high and low lead groups IQ full scale 4.5, verbal 4.6, performance 3.8. Significant trend observed indicating a dose-response relationship.
Lowell, Mass. (1981) [89]	Dentine	1273 children Five groups: ≤6.4, 6.5-8.7, 8.71-12.01-18.1, ≥18.2 $\mu g\ g^{-1}$ Selected 215 children from 447	Eleven teacher behaviour ratings grouped into 5 clusters	SES, birthweight, mother's education	Significant trend for behaviours; distractable, disorbanised and frustrated, a dose-response relationship.
West German (1983) [126]	Whole teeth	26 matched pairs low lead <3 $\mu g\ g^{-1}$ high lead > $\mu g\ g^{-1}$ Original sample 1238 children	WISC-R visual motor integration gross motor integration	Matched for age, sex, father's occupation (other factors similar for two groups)	Near significant difference in IQ, performance. 6 points ($p = 0.08$), full scale 7 points ($p = 0.09$); visual motor integration significantly different (GFT test); verbal IQ (5 pts) and gross motor integration not significant.
(1983) [127]	Whole teeth	Three groups <4.2 $\mu g\ g^{-1}$, 36 5.8-7.2 $\mu g\ g^{-1}$, 56 >9.8 $\mu g\ g^{-1}$, 23 selected from 317 children out of 3669	WISC-R visual motor integration Vienna reaction time; behaviour ratings	Sex, age, labour duration, socio-hereditory background (school type & father's occupation)	A difference in IQ's but not significant, visual motor integration (GFT) significantly different, some parent behaviour ratings significantly different, not for teacher ratings.

Table 16.6 continued

Study	Lead Measure	Sample	Tests	Confounding variables	Results
Australia (Sydney) (1979) [43]	Blood Hair	Four school areas 1200 children	Questionnaire to parents and teachers	None, pica not associated lth lead	Significant correlations in behavioural and anti-social behaviour.
London (1983) [118]	Whole tooth crown	Three groups <2.5 $\mu g\ g^{-1}$ 5.0-5.5 $\mu g\ g^{-1}$ >8.0 $\mu g\ g^{-1}$ 403 from 3890 from a possible 6875 children	WISC-R, word reading, maths., seashore rhythm, visual seuqential memory subset, sentence memory, shape copying, behaviour ratings	Mother's IQ, parental educ., interest, family characteristics, social background, birth condition, developmental delay, marital relationship, mother's mental state, sex, age, tester, - controlled when required.	Non-significant IQ differences (verbal 2.3, performance 1.8, full scale 2.3, word reading 4.2) after control for C.V. Show a consistent trend in decrease with increase in lead.
Chicago (1983) [91]	Blood	Three groups <25 $\mu g\ g^{-1}$ 30-40 $\mu g\ g^{-1}$ 41-60 $\mu g\ g^{-1}$ 218 children	WPPSI	None, groups relatively homogenous	Statistical significant differences for high lead with other two groups, in verbal productivity, perceptual and visual motor function.
New Zealand (Dunedin) (1988) [117]	Blood	579, 11 yr. four groups <7, 7-10, 10-13, >13 $\mu g\ dl^{-1}$	WISC-R, spelling, reading, behaviour	SES, no correl. with PhB, mother's ability	IQ not significantly associated with PhB, but reading, spelling and behaviour were.
London (1985,87) [100,101]	Tooth crowns	<1.0-34 $\mu g\ g^{-1}$ 403 from 3890	Tests as for ref. 118	Parental and social factors	Non-signif. IQ, mothers IQ main determinant Boys IQ/lead assoc. remained signif.
USA (1987) [113]	Blood	4519 from NHANES II survey	Hearing threshold	Various ear conditions SES, urbanization	Signif. increase in hearing threshold with lead also early infant activities, e.g. sit walk.

Table 16.6 continued

Study	Lead Measure	Sample	Tests	Confounding variables	Results
New Zealand (Christchurch) (1988) [40,41]	Dentine	<1.0->20.0 µg g⁻¹ 664-888 children 8-9 yrs.	IQ, Burt reading test, teacher ratings of school performance, teeth sampling behaviour	Parent educ. level, SES family environ., perinatal history, child's educ. exper.,	IQ/lead assoc., but not significant with confounders but stat. signif. school performance, and attentive/restless behaviour.
Birmingham (UK) (1984) [50]	Blood	187 pre-school 15.6 µg dl⁻¹	Child behaviour, psychomotor, cognitive	SES, parents educ., marital situation, age child's activities	Non-signif. IQ/lead, after controlling for confounders.
Birmingham (UK) (1988) [51]	Blood	201 5.5 yr. olds	Reaction times, motor skills, behaviour, IQ mother's IQ vigilance	SES, parents mental health, life events marital situation	Non-signif. IQ/lead assoc., marginally based on father's occupation, some motor skills relate to lead levels.
London (UK) (1986) [66]	Blood	194, 7-24 µg dl⁻¹	IQ, educ., attain., teacher ratings of performance	SES (occupation), age	Non-signif lead/IQ relationship after use of confounders.
Boston (USA) (1984) [cf. 28]	Cord blood	249; 1.8, 6.5, 14.6 µg dl⁻¹ three groups	Bayley MDI	Yes	Signif association, cord blood lead and reduced MDI measure.
Cincinnati (USA) (1986) [cf. 28]	Blood mothers infants	8.0 µg dl⁻¹ 4.5 µg dl⁻¹	Bayley MDI, PDI	Race, SES, home environ., tobacco & alcohol use, natal problems	Signif. assoc. pre-natal blood lead and MDI measure.

The blood lead levels obtained in the USA during the NHANES II survey were studied in relation to the hearing threshold of 4519, 4-19 year olds. A significant association was discovered, which showed a higher threshold (frequency) existed for the people with higher lead levels. Also, using the same blood lead data, significant associations were found with the age a child first sat up, walked and spoke, as well as evidence for hyperactivity [113].

Studies in West Germany Two investigations have been carried out in West Germany [53,124-127], in which dentine lead was used as the lead marker. From a sample of 1238 children, 904 incisors were analysed from 604 children, eventually 26 pairs matched for age, sex and fathers' occupation (SES) were obtained. Lower IQ's were found for the high lead group, but the difference with the low lead group did not reach statistical significance. The small sample may have had something to do with this.

In a second study at Stolberg, in a mining area, [124,127] a sample of 3669 children were used. The dentine lead of 115 children were divided into three groups. Some blood lead levels were also measured. Verbal IQ decreased, 117, 115, 109 with increasing dentine lead ($p<0.1$), whereas other IQ measures were not significant, though the trend was in the same direction. However, after correcting for the CV's, the verbal IQ's differences became not significant.

Studies in the United Kingdom A large study carried out on London children [118], was both well planned and detailed. From a total population of 6875, 6-7 yr old children, from 168 London schools, 4105 children provided teeth of which the whole tooth crowns were analysed. A sub-sample of 403 children were then studied in detail. The groupings within this sample were: low lead (<2.5 µg g⁻¹) 145, medium lead (5.0-5.5 µg g⁻¹) 103, and high lead (>8.0 µg g⁻¹) 155. A number of neurologic and psychometric tests were carried out on the sub-sample. For the lead groups, unadjusted for covariates, the three IQ scores were significantly different for the high and low lead groups, as was a word reading test and one block of 'reaction time without delay' tests. In addition the results showed the trend for IQ; low lead < medium lead < high lead. Re-calculation of the data using the CV's removed the statistical significance. The variance in the tooth lead was accounted for by family cleanliness, pica, years the child sucked their thumb, mother's smoking habit, proximity to waste land, age of house and child's play space. If anything the study may have over compensated for the confounding factors.

A number of other studies have been completed in the UK. The work described above [118] has been reevaluated using the dentine lead as a continuous variable rather than grouped. Again no association was found between tooth lead and child's IQ. Parental IQ had the major influence on the the child's IQ. However, there was a small significant association, after allowing for CV's, between tooth lead and the IQ of boys. This was an unexpected result, and needs to be replicated [100,101].

An earlier study of children in London, living near a smelter (Table 16.4) [63,130], found an association between blood lead and IQ. This was replicated [66], this time using children living near a major road system. The results this time did not reveal any association, though children of manual workers did have a non-significant trend of decreasing IQ and increasing blood lead. One reason may have been the small sample of 87 children. The difference between this result and the earlier study, may have been in the SES mix of the samples, as more children of middle class families were included in the second study [66].

Two studies have been carried out on Birmingham children, 187 preschoolers, and 201 children 5.5 years old. The results of both studies indicated no association with blood lead and IQ, though for the older group a non-significant trend was found. In some neuropsychological tests significant associations were observed [50,51].

Studies in the South Pacific Three studies have been carried out in the South Pacific. A sample of 1200 children, in Sydney, Australia, were studied using capillary blood and hair for lead measurement [43]. The principal finding was that proximal hair lead related to behavioural and antisocial problems most strongly. Blood lead and behavioural factors were also significantly related.

In Dunedin, New Zealand, as part of a Child Multidiscipline Health and Development Study, 574 eleven year old children were studied using blood lead as the lead marker [117]. Whereas IQ was not significantly associated with lead, a number of cognitive functions and attention/behavioural ratings were significantly associated, after controlling for the confounding variables.

A larger study of children (664 to 888 depending on the neuropsychological measure) has been carried out in Christchurch, New Zealand The children were aged 8 and 9 years and dentine lead was used as the lead measure [40,41]. The lead measure was treated as a continuous variable, and allowance was made for the intrinsic variability of the sample. As for many other studies a trend of decreasing IQ and increasing lead was observed, but after controlling for CV's the trend was not statistically significant. Teacher ratings, however, of school performance remained significant [40]. Maternal and teacher ratings of inattention and restlessness were found to have a small, but consistent, and significant association with the dentine lead variable [41].

Mechanism

As yet there is no clear picture of the mechanism by which the lead can influence the neurological functioning of children. One possibility [12,81] is that δ-ALA (δ-aminolevulinic acid), which is raised in the blood because of the inhibition of haem synthesis by lead, is a neurotoxin and can cross the blood-brain barrier. The δ-ALA could be a weak antagonist to the neuro-transmitter γ-aminobutyric acid (GABA), $HO_2C\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}NH_2$. The chemical structure of GABA and δ-ALA, $HO_2C\text{-}CH_2\text{-}CH_2\text{-}CO\text{-}CH_2\text{-}NH_2$ are not unrelated, and the latter may mimic the GABA as a false neuro-transmitter. GABA is believed to be an important neuro-transmitter in the cerebral cortex and lead may inhibit its metabolism. Both GABA, and maybe the neurotoxic effects of δ-ALA, appear to be mainly associated with areas such as stress, anxiety and hyperactivity, and if this is so it tends to fit in with the results of the studies discussed above.

In conclusion it may be said that, overall from the large number of different studies the weight of evidence does suggest an association between low level lead exposure and neurological functioning of children. The lead may slightly affect the IQ of children, but usually not significantly. This may because IQ is not the best outcome to measure in relation to lead. It does seem however, that behaviour, restlessness, and attentiveness are more clearly and significantly associated with lead in children. This could be considered a serious situation, because such behaviour problems are not conducive to children learning irrespective of the IQ. The affect of lead on the human race has been with us for centuries [94] because of its wide use in industrialized societies. Whether or not the situation is any worse today has been debated, but it does appear from the work described above that the urban population at least, is being influenced by the neurotoxicity of lead.

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