ASSESSMENT CONCLUSIONS AND SUGGESTIONS OF WHO'S INTERNATIONAL EMF PROJECT

WHO"国际电磁场计划"的评估结论与建议

杨新村　李毅　译

World Health Organization

中国电力出版社

内 容 提 要

本书以中英文形式首先介绍了WHO的重要官方文件《电磁场和公共健康：曝露于极低频场（Fact Sheet No. 322）》，该官方文件阐明了WHO“国际电磁场计划”对极低频场与公共健康的全面评估结论与政策建议；其次介绍了《极低频场环境健康准则（EHC No. 238）》的第一章，WHO针对极低频场生物影响科学文献进行了全面复核，阐明了极低频场健康风险评价的总体结论，并向各国政府当局提出了健康保护、预防性措施与政策建议。

本书可供政府环保、卫生、建设、规划、法律相关部门的决策、管理人员；电磁环境保护、疾病控制与预防，以及生物电磁学领域内的研究人员；从事电力和电气规划、设计、建设、运行的相关管理人员和技术人员阅读使用。也可供关心电磁环境与健康关系的高等院校师生和具有一定专业基础的公众参考。

图书在版编目（CIP）数据

WHO“国际电磁场计划”的评估结论与建议/世界卫生组织；杨新村，李毅译. —北京：中国电力出版社，2008

ISBN 978-7-5083-6767-5

Ⅰ. W… Ⅱ. ①世…②杨…③李… Ⅲ. 电磁场-环境影响-研究 Ⅳ. X123

中国版本图书馆CIP数据核字（2008）第021858号

北京市版权局著作权合同登记

图字：01-2008-1027

本版图书包括 *Environmental health criteria 238*：*Extremely low frequency fields* 的 *1~20* 页内容，和 *the World Health Organization Fact Sheet No. 322*：*Electromagnetic fields and public health*：*Exposure to extremely low frequency fields*，均为世界卫生组织2007年出版

中国电力出版社出版、发行

（北京三里河路6号 100044 http://www.cepp.com.cn）

北京博图彩色印刷有限公司印刷

各地新华书店经售

*

2008年3月第一版 2008年3月北京第一次印刷

787毫米×1092毫米 16开本 4.5印张 66千字

印数0001—5000册 定价**12.00**元

前　言

针对公众对电磁场健康影响的关注，世界卫生组织（WHO）自1996年开始，组织60多个国家及多个国际组织，开展全球性的“国际电磁场计划”研究，历时十年，目前已完成了极低频场的全面健康风险评估，并在一系列重要官方文件中，阐明了该研究结论与建议。

本书共分为两个部分，分别介绍了WHO于2007年6月正式发布的《电磁场和公众健康：极低频场曝露（Fact Sheet No. 322》和《极低频场环境健康准则（EHC No. 238）》的第一章（原文共12章，第一章是其他各章节研究内容和结论的集中概括）。第一部分阐明了WHO“国际电磁场计划”对极低频场公共健康风险的全面评估结论与政策建议。第二部分总结了WHO对极低频场生物效应科学文献复核的结论与意见；阐明了WHO极低频场健康风险评价的总体结论；向各国政府当局提出了健康保护、预防性措施与政策建议。

在本书的翻译出版过程中，得到了世界卫生组织出版部、辐射和环境卫生处的支持与帮助，国内多位电磁环境保护相关领域的专家也对译文内容进行了审读并提出了宝贵意见，在此一并致以诚挚的谢意。

本书可供政府环保、卫生、建设、规划、法律相关部门的决策、管理人员；电磁环境保护、疾病控制与预防，以及生物电磁学领域内的研究人员；从事电力和电气规划、设计、建设、运行相关的管理人员和技术人员阅读使用。也可供关心电磁环境与健康关系的高等院校师生和具有一定专业基础的公众参考。

限于译者水平，书中难免存在错误或不妥之处，敬请读者批评指正。

译　者

2008年2月

目　录

电磁场和公众健康：极低频场曝露

（Fact Sheet No. 322）

电力已经成为我们日常生活中不可缺少的一部分。只要电在传输，邻近输电线路和用电设备的周围就存在电场和磁场。曝露于这些极低频（ELF）电场和磁场（EMF）是否会产生有害的健康后果？这个问题自 20 世纪 70 年代后期起就已提出。从那时开始，人们做了很多研究，成功地解决了一些重要的问题，并缩小了进一步研究的关注范围。

1996 年，世界卫生组织（WHO）建立了“国际电磁场计划”，以调查与电磁场相关的潜在健康风险。WHO 的一个工作组最近对极低频场的健康影响进行了总结。

本 Fact Sheet 以该工作组的结论为基础，更新由 WHO 主办的国际肿瘤研究机构（IARC）于 2002 年和由国际非电离辐射防护委员会（ICNIRP）于 2003 年发布的有关极低频电磁场健康影响的观点。

1　极低频场源和居民曝露

电场和磁场存在于有电流流过的地方，例如电力线和电缆，民房布线和用电设备。电场的产生源于电荷，以伏特每米（V/m）计量，可被木头、金属等普通材料屏蔽。磁场起源于电荷的运动（例如电流），以特斯拉（T）或更常用的毫特斯拉（mT）、微特斯拉（μT）表示。在有些国家，还常用另一个单位高斯（G）表示（10000G = 1T）。磁场不能被大多数普通材料所屏蔽，它很容易就能穿过这些材料。电场和磁场在源头附近最强，随距离增加而衰减。

大多数电力都以 50 或 60 周波每秒（或赫兹，Hz）的频率运行。在某些用电设备附近，磁场水平可能会有几百微特斯拉。在电力线下方，磁场大约为 20μT，电场大约为几千伏特每米。不过，在民房中，平均工频磁场就低得多了，在欧洲大约为 0. 07μT，在北美约为 0. 11μT。居民家中平均的电场值约几十伏特每米。

2　工作组评价

2005 年 10 月，WHO 召开了科学专家工作组会议，对曝露于 0 ~ 100kHz 频率范围内的极低频电场和磁场可能存在的任何健康风险进行评定。2002 年，

IARC 在检查与癌症有关的证据时，工作组就仔细研究了大量健康影响的证据，并更新了这些关于癌症的证据。工作组的结论和建议发表在 WHO 的环境健康准则（EHC）专论中（WHO，2007）。

按照标准的健康风险评价程序，工作组的结论是，对于公众通常遇到的极低频电场水平，不存在实际健康问题。本 Fact Sheet 接下来的部分，主要论述曝露于极低频磁场中的影响。

3 短期影响

对于高水平磁场曝露（显著超过 100μT）产生的生物效应，已是确定的了，可由公认的生物物理机制予以解释。外部极低频磁场在人体内感应出电场和电流，当场强非常高时，会导致神经和肌肉的刺激，并引起中枢神经系统中神经细胞兴奋性的变化。

4 潜在的长期影响

大量针对极低频磁场曝露长期风险的科学研究，都将重点放在儿童期白血病上。2002 年，IARC 发表了一本专论，将极低频磁场归类为“怀疑对人类致癌的”。被列为该类的物质，其在人类致癌性方面存在有限的证据、在实验动物致癌性方面存在不足的证据（该类物质还包括咖啡和焊接烟雾）。该分类是根据对流行病学研究的集合分析而作出的，这些研究在住所中工频磁场平均曝露超过 0. 3 ~ 0. 4μT 与儿童期白血病患病率两倍增长之间，显示了一致的关联。工作组的结论是，从那之后的其他研究，都没能改变这种分类的状况。

但是，流行病学的证据被方法问题所削弱，例如潜在的选择性偏倚。另外，也没有可接受的生物物理机制来说明低水平曝露和引发癌症有关。因此，如果说低水平场曝露会产生什么影响，就必须先通过我们至今还不知道的一个生物机制来解释。此外，动物研究结果大都是阴性的。因此，总体权衡，与儿童期白血病有关的证据不足以认定其存在因果关系。

儿童期白血病是一种较为罕见的疾病，2000 年全球总的新病例量大约是 49000 例。住所中平均磁场曝露超过 0. 3μT 的很少见，患病儿童中大约只有

1% ~ 4% 生活在这种状况下。如果说磁场曝露和儿童期白血病之间的关联是有因果性的，那以 2000 年的数值计算，全世界因磁场曝露而导致的病例数大约是每年 100 ~2400 例，代表着那年总病例的 0. 2% ~4. 95%。因此，如果说极低频电磁场确实增加了这种疾病的风险，从全球角度考虑，极低频电磁场曝露对公众健康的影响也是有限的。

人们还进行了大量其他与极低频磁场曝露可能有关的有害健康影响研究，包括其他儿童癌症、成人癌症、忧郁症、自杀、心血管紊乱、不育、发育障碍、免疫系统变异、神经生物影响和神经退变性疾病。WHO 工作组的结论是，支持极低频磁场曝露和所有这些健康影响有关系的科学证据，都比儿童期白血病的弱得多。在一些研究中（例如心血管疾病和乳癌），证据显示极低频磁场不会引起这些疾病。

5 国际曝露导则

与短期、高水平曝露有关的健康影响已是确认的了，并已成为两个国际曝露限制导则（ICNIRP，1998；IEEE，2002）制定的基础。当前，这两个机构认为，关于长期、低水平极低频场曝露健康影响可能性的科学证据，不足以证明需要降低这些量化的曝露限值。

6 WHO 的指导意见

高水平、短期曝露于电磁场产生的有害健康影响，已经科学地确认了（ICNIRP）。为保护工人和公众免受这些影响而制定的国际曝露导则，应该为政策制定者采纳。电磁场防护程序应包括对可能超出限值的曝露源进行曝露测量。

关于长期影响，因为极低频磁场曝露和儿童期白血病之间的关联证据弱，因此从健康角度减少曝露所得的益处也是不清楚的。针对这种状况，提出以下建议：

政府和企业应追踪科学，促进研究计划，以减少有关极低频场曝露健康影响的科学证据的不确定性。通过极低频风险评估程序，可发现知识的缺陷，这些可作为新研究项目的基础。

鼓励各成员国与所有的利益相关者建立有效和公开的信息交流计划，以实现知情决策。这包括在产生极低频电磁场设施的规划过程中，加强企业、当地政府和市民之间的协调和咨询。

当建设新的设施和设计新设备，包括家用电器时，应探索低成本的减少曝露的方法。合理的减少曝露的措施可能会因国家而不同，但是，采纳武断的低曝露限值的政策是没有根据的。

7 其他读物

（1）WHO 极低频场环境健康准则（EHC No. 238）. 日内瓦，WHO，2007.

（2）评估对人类致癌性风险的 IARC 工作组 . 非电离辐射，第一部分：静态、极低频（ELF）电场和磁场 . 里昂，IARC，2002（关于对人类致癌性风险评估的专论，80）.

（3）ICNIRP——国际非电离辐射防护委员会 . 曝露于静态和低频电磁场，生物效应和健康后果（0 ~ 100kHz）. Bernhardt JH 等，Oberschleissheim，国际非电离辐射防护委员会，2003（ICNIRP13/2003）.

（4）ICNIRP——国际非电离辐射防护委员会（1998）. 限制时变电场、磁场和电磁场（300GHz 以下）曝露的导则 . 健康物理学 74（4），494 ~ 522.

（5）IEEE 标准协调委员会 28. 关于人体曝露到电磁场（0 ~ 3kHz）的安全水平的 IEEE 标准 . 纽约，IEEE（电气和电子工程师协会）2002（IEEE 标准 C95. 6 － 2002）.

World Health Organization

ASSESSMENT CONCLUSIONS AND SUGGESTIONS OF WHO'S INTERNATIONAL EMF PROJECT

WHO"国际电磁场计划"的评估结论与建议

极低频场环境健康准则

（EHC No.238）

——总结和进一步研究的建议

《环境健康准则（EHC）》专著阐述了曝露于极低频（ELF）电场和磁场可能的健康影响，复核了极低频场的物理特性以及曝露源和测量。但是，其主要目的是对曝露于极低频场生物影响的科学文献进行审核，以评定曝露于这些场的健康风险；并利用这些对风险的评估，向各国政府当局提出健康保护计划的建议。

本专著针对的频率范围是 0Hz ~ 100kHz。到目前为止，已进行的绝大部分研究都是针对工频（50 或 60Hz）磁场，其中很小一部分也研究了工频电场。另外，还有很多研究是关于甚低频（VLF，3 ~ 30kHz）场、用于磁共振成像的投切陡波磁场，以及由视频显示单元和电视机产生的弱甚低频场。

本文是对 EHC 专著各个章节的主要结论和建议的总结，也是对健康风险评估的总体结论。专著中用以描述给定健康后果的证据强度的术语如下：当某证据局限在某一单项研究，或一批研究的设计、实施或解释中还存在很多不能回答的问题时，这种证据被定义为“有限的（limited）”。当存在重要的定性或定量上的局限性，使研究不能被理解为显示了某影响是存在还是不存在时，或是没有可用的数据时，这种证据就被定义为“不足的（inadequate）”。

本专著也识别了主要的知识缺陷和填补这些缺陷需要进行的研究，详见“研究建议”部分。

1　总结

1.1　源、测量和曝露

在发电和通过电力线与电缆输电或配电时，或在用电设施使用电时，就存在电场和磁场。由于电力是我们现代生活不可或缺的一部分，这些场在我们环境中无处不在。

电场强度的单位是伏特每米（V/m）或千伏每米（kV/m）。磁场用磁通密度（即磁感应强度）表示，单位是特斯拉（T），或是更常用的毫特斯拉（mT）、微特斯拉（μT）。

对于工频磁场的居民曝露，世界各国的差异都不太大。居民家中的几何平均磁场，在欧洲约为 0.025 ~ 0.07μT，在美国约为 0.055 ~ 0.11μT。家中电场的平均值一般为几百伏特每米。在一些用电设施附近，瞬时磁场值可为几百微特

斯拉。电力线附近的磁场差不多为 20μT，电场约为几千伏每米。

几乎没有儿童在居住环境为 50 或 60Hz 磁场中的时间平均曝露超过与儿童期白血病发病率增加相关联的曝露水平（见 1.10 部分）。大约 1% ~4% 的儿童的平均曝露超过 0.3μT，仅 1% ~2% 的儿童的平均曝露超过 0.4μT。

职业曝露绝大部分指的是工频场，也可能包括一些其他频率的作用。“电气职业”工作场所的平均磁场曝露高于其他职业（例如办公室工作）。电工和电气工程师的磁场曝露约为 0.4 ~0.6μT，电力线路工人约为 1.0μT，焊接工、铁路机车驾驶员和缝纫机操作工的曝露最高（超过 3μT）。工作场所最大磁场曝露可达约 10mT，这些总是与存在大电流导线有关。在供电行业，工人的电场曝露可达 30kV/m。

1.2 人体内的电场和磁场

极低频电磁场曝露，会在人体中感应出电场和电流。剂量测定学中阐述了外部场和人体中感应电场及电流密度之间，或同其他与电磁场曝露相关的参数之间的关系。由于人体中的感应电场和电流密度与神经和肌肉等易兴奋组织的激励有关，因此特别引人关注。

人类和动物的身体会显著地干扰极低频电场的空间分布。在低频时，人体是良导体，其外部被干扰的电力线近似地与人体表面垂直。处于曝露中的人体表面会感应出交变电荷，交变电荷继而在人体中感应出电流。关于人类曝露于极低频电场的剂量学关键特性如下：

- 人体内的电场与其外部电场相比，通常要小 5 ~6 个数量级。
- 曝露于垂直场时，感应场的主要方向也是垂直的。
- 对于一个给定的外部电场，最强的感应场出现在通过脚与地面良好接触（电气接地）的人体中，最弱的感应场出现在与地面绝缘（处于“自由空间”）的人体中。
- 与地面良好接触的人体中的电流总量，取决于人体的大小和形状（包括姿势），而不是取决于组织的电导率。
- 各种器官和组织中感应电流的分布，取决于这些组织的电导率。
- 感应电场的分布同样受到电导率的影响，但比感应电流受到的影响程度弱。

- 也有一种情况下，人体中的电流是由于接触电场中的导体而感应出来的。

对磁场来说，组织的渗透率和空气相同，因此组织中的场与外部场相同。人类和动物的身体不能对磁场造成显著的干扰。磁场产生的主要作用是在导电组织中产生电场法拉第感应和相应的电流密度。关于人类曝露于极低频磁场的剂量学关键特性有：

- 感应电场和电流取决于外部磁场的方向。整体而言，当磁场从身体由前至后穿过人体时，人体中的感应电场最大。但对某些个别器官来说，最高的电场值出现在磁场从一侧穿至另一侧时。
- 当磁场的方向与人体的垂直轴平行时，感应出的电场最弱。
- 对于一个给定场强和方向的磁场，人体越大，感应的电场也越高。
- 感应电场的分布受到各种器官和组织电导率的影响，而感应电流密度的分布受到的这种影响是有限的。

1.3　生物物理机制

对于已经提出的各种极低频电场和磁场的直接或非直接作用机制的可能性进行了检验。重点是检验场曝露在生物过程中产生的“信号”是否能从内在的随机噪声中识别出来，以及该机制是否是对科学原理和现有的科学知识的一种新认识。许多机制只是在场强超过一定强度时才可能是合理的。不过，只要是符合基本科学原理，缺乏已验证的合理机制并不意味着排除了即使是很低的场水平下存在健康影响的可能性。

在大量已提出的场与人体直接相互作用的机制中，有三种在较低场水平下比其他机制有突出潜在作用的场的机制：神经网络中的感应电场、基团配对和磁铁物机制。

因极低频电场或磁场曝露而在组织中产生感应电场，当内部场强超过几伏特每米时，会以一种从生物物理学角度似乎合理的方式，直接刺激单个有髓神经纤维。与单个细胞相比，更弱的场也会影响神经网络中的突触传输。多细胞生物体通常采用这种神经系统信号处理方式，以探测微弱的环境信号。有人建议对神经网络有区别地采取较低的 1mV/m 的限值，但根据现有证据，阈值取 10 ~ 100mV/m 看来更合适。

按照基团配对机制，磁场会影响某些特殊类型的化学反应，通常会在低水

平场中提高反应自由基的浓度（这种提高在小于 1mT 的磁场中可观察到），而在高水平场中降低它们的浓度。有一些证据表明这种机制同候鸟迁徙中的导航有关联。根据理论分析，同时因为极低频磁场和静磁场产生的变化很相似，人们认为远小于约 50μT 地磁场的工频场，不像具有明显的生物学显著性。

在动物和人的组织中，存在着磁铁物晶体，即各种形状的小氧化铁铁磁晶体，尽管只有痕量。与自由基对相同，它们也与迁徙性动物的定向和导航有关，只不过人脑中痕量的磁铁物不足以探测到微弱的地磁场。基于极端假设的计算显示极低频场对磁铁晶体产生影响的低限是 5μT。

场的其他直接生物物理学作用，例如断开化学键，对带电微粒产生的力，以及各种窄带“共振”机制，都不能提供在公众和职业环境中遇到的场水平下，可能产生作用的合理解释。

至于非直接影响，可以觉察到电场感应出的表面电荷，它可能导致在触摸到导体时，产生痛感的微电击。接触电流也可能发生在儿童接触例如居室中浴缸的龙头时。这会在骨髓中产生出有可能超出背景噪声水平的小电场。但是，这是否形成一种健康风险还是未知的。

高压电力线会因电晕放电而产生带电离子云，有人认为这些离子云会增加空气污染物在皮肤和体内呼吸道表面的沉积，可能对健康有害。但是，即便如此，甚至对极端曝露的个体，从长期健康风险来看，电晕离子的影响估计是很小的。

对于人类通常遇到的曝露水平，上述三种直接机制中，没有一种可认为是导致发病率升高似乎可信的原因。事实上，仅在场水平数量级较高时，且非直接机制尚未被充分研究时，这些机制才成为似乎可能的。缺乏可确认的似乎可信的机制，并不能排除有害健康影响的可能性，但是，它确实提出了需要更强的生物学和流行病学证据的必要。

1.4 神经行为

曝露于工频电场会因表面电荷而产生可明确定义的生物反应，其反应程度可从“有感觉”到“烦恼”。这些反应取决于场强、周围环境条件和个体的敏感性。能让 10% 的志愿者直接感觉到的场强阈值是 2～20kV/m，5% 的志愿者对 15～20kV/m 的电场感到烦恼。在 5kV/m 的场中，人对地的火花放电会让 7% 的

志愿者感到疼痛。带有电荷的物体通过接地的人的放电阈值，取决于物体的尺寸，因此需要专门的评估。

高强度、快脉冲磁场会刺激外围或中枢神经组织。这种影响在磁共振成像（MRI）过程中会出现，也被经颅磁刺激（TMS，一种疗法）所利用。产生直接神经刺激的感应电场强度阈值可低至几伏特每米。该阈值对于几赫兹至几千赫兹的频率范围都是一样的。癫痫病人或易患癫痫病的人，可能对中枢神经系统（CNS）感应极低频电场更敏感。此外，对 CNS 电刺激的敏感度，可能与家族癫痫病史，以及服用三环的抗抑郁药、安定剂和其他易引发癫痫病的药物有关。

视网膜是 CNS 的一部分，可能影响其功能的极低频磁场曝露水平比引起直接神经刺激的磁场水平微弱得多。产生的闪烁灯光感觉称为磁光幻视，它是由感应电场对视网膜中电兴奋细胞作用的结果。视网膜中细胞外液中感应电场强度的阈值在 20Hz 时约为 10 ~ 100mV/m。但是，关于该阈值还有很多不确定因素。

志愿者研究中，其他神经行为影响的证据，例如对人脑电活动、知觉、睡眠、超敏性和情绪的影响，都是不明朗的。一般来说，这些研究都是在低于引起上述影响的曝露水平下进行的，且已获得的证据最多也只是不明显和短时影响的。产生这种反应所必需的条件，在目前还是不明确的。有一些证据显示，场会影响反应时间，降低一些感知任务完成的精确度，对于脑总体电活动的研究结果也支持这一点。调查磁场是否会影响睡眠质量的各项研究，其结果是不一致的，部分原因可能是研究的设计有区别所致。

有人声称总体上对电磁场超敏感，但是，双盲刺激研究的证据显示，所报道的各种症状与电磁场曝露无关。

对于极低频电场和磁场曝露会导致抑郁症或自杀的说法，仅有不一致和无确定结果的证据。因此，证据可考虑为是不足的。

关于动物曝露于极低频场可能对神经行为功能产生的影响，已经按不同的曝露条件从许多方面进行了探索。几乎没有可确认的影响。有令人信服的证据表明，动物能觉察到工频电场，最有可能是表面电荷影响的结果，可能是暂时的唤醒作用或轻微的压力感。大鼠可觉察到的范围是 3 ~ 13kV/m。啮齿动物对超过 50kV/m 的场强表现出厌恶。其他可能与场有关的变化都不是很明确，实验室研究仅得到了不明显和暂时性影响的证据。有一些证据显示，磁场曝露可

能会调整脑中吗啡和胆碱能神经传输系统的功能。对痛觉缺失以及对获得和完成空间记忆任务的影响问题的研究结果，支持了这一点。

1.5 神经内分泌系统

志愿者研究、居所及职业流行病学研究显示，工频电场或磁场不会对神经内分泌系统产生有害影响。这特别表现在神经内分泌系统中特殊荷尔蒙的循环水平，包括由松果体释放出的褪黑激素，也表现在由脑下垂体释放出的大量与身体新陈代谢和生理机能控制有关的荷尔蒙。有时观察到褪黑激素的释放时间因曝露特性不同而有不明显的区别，但是这些结果并不一致。要通过改变环境和生活方式等可能影响荷尔蒙水平的因素来排除可能的混淆，是非常困难的。大多数关于极低频曝露对志愿者夜间褪黑激素水平影响的实验室研究，在采取措施控制可能产生的混淆后，都发现没有影响。

在大量调查工频电场和磁场对大鼠松果体和血清褪黑激素水平的影响的动物研究中，一些报告称曝露会抑制夜间褪黑激素的分泌。在早期高达 100kV/m 的电场曝露研究中首次观察到的褪黑激素水平的变化不能被再现。一系列较近期的研究显示了循环极化磁场会抑制夜间褪黑激素水平，但上述结果因将曝露动物和历史对照进行了不适当的比较而被削弱。其他啮齿动物试验的数据包括了从几个微特斯拉到 5mT 的场强水平，结果也是模棱两可的。因为有些结果显示出褪黑激素被抑制，而另一些显示出没有变化。在季节性繁殖动物中，工频场曝露对褪黑激素水平以及由褪黑激素决定的繁殖状况的影响的证据，绝大部分都是否定的。尽管利用两个动物进行的初步研究报道不规则和间歇性的曝露会抑制褪黑激素，但是，在非人类灵长类动物长期曝露于工频场的研究中，没有发现令人信服的影响。

尽管体外实验研究相对来说进行得很少，但极低频场曝露对分离的松果体腺中褪黑激素产生和释放的影响是各不相同的。有关极低频曝露会干扰褪黑激素对体外肺癌细胞的作用的证据，是非常令人感兴趣的。但是，这个实验系统具有不利的缺陷：细胞系在培养中经常显示出基因型和表现型的连续变异，这妨碍了各实验室间的可转移性。

除了刚开始曝露在强度高到可以察觉到的极低频电场中可能出现的短时紧张外，极低频电场对各类哺乳动物样本垂体—肾上腺轴中与压力有关的荷尔蒙

没有一致的影响。类似地，虽然相关研究做得很少，但极低频电场对生长荷尔蒙或参与控制新陈代谢活动的荷尔蒙水平，以及与繁殖和性成长控制相关的荷尔蒙的水平的影响，大部分都是阴性的，或是没有观察到一致性的影响。

总之，这些数据不能表明，极低频电场和/或磁场会以对人类健康产生有害作用的方式，影响神经内分泌系统，其证据因此被认为是不足的。

1.6 神经变性疾病

有人假设极低频场曝露与一些神经变性疾病有关。关于极低频场和帕金森病以及许多硬化症关系的研究进行得不多，没有显示极低频场和这些疾病之间有关系的证据。关于阿尔茨海默病以及肌萎缩侧索硬化症（ALS），已发表了许多研究结果。一些报告提示，从事电力职业的人员，ALS 的风险可能会增加。直到现在，还没有能够解释这种关联的生物机制，尽管这可能因与电力职业相关的混杂因素（例如触电）而形成。总之，有关极低频曝露和 ALS 之间的关系的证据被认为是不足的。

关于极低频曝露和阿尔茨海默病关系的少量研究，结果是不一致的。但是，关注于阿尔茨海默病发病率而不是死亡率的高质量研究，未能表明这种关联。总而言之，关于极低频曝露和阿尔茨海默病之间有关联的证据是不足的。

1.7 心血管疾病

不论短期和长期曝露的实验研究都表明：触电具有明显的健康危害，但在通常遇到的环境或职业曝露水平中，其他与极低频场有关的有害的心血管影响是不大可能发生的。尽管有关于各种心血管变化的文献报道，但是绝大部分影响是小的，且研究本身和各种研究之间的结果也不一致。有一个例外，即所有关于心血管疾病发病率和死亡率的研究中，没有一项显示与曝露有关。在曝露和心脏自律控制改变之间是否存在特殊的关联，仍是推测性的。总之，证据不支持极低频曝露和心血管疾病之间有关联。

1.8 免疫学和血液病学

有关极低频电场或磁场曝露对免疫系统组成部分的影响，总体而言是不一致的。许多细胞群和功能标记都不受曝露的影响。但是，在一些人类研究中，

在 10μT～2mT 的场中，观察到自然杀伤细胞有所改变，细胞数量增、减的情况都有；总白细胞数量也有所改变，或是保持原样，或是有所减少。动物研究中，在雌性小鼠上观察到自然杀伤细胞活动有所减少，而在雄性小鼠以及所有性别的大鼠上都没有观察到。白细胞数量的改变显示出不一致性，在不同的报告中，有的显示减少了，有的保持原样。动物曝露的范围更大一些，从 2μT～30mT。解释这些数据潜在健康影响的难点在于，曝露和环境条件的变化太大了，实验对象相对较少，以及观察终点涉及范围太大。

有关极低频磁场对血液系统影响的研究开展得很少，在评估白细胞数量差异的实验中，曝露范围在 2μT～2mT。不论在人类或动物研究中，极低频磁场或极低频电场结合磁场的急性曝露，都没有发现一致的影响。

总之，极低频电场或磁场对于免疫和血液系统影响的证据，被认为是不足的。

1.9　生育和生长

整体而言，流行病学研究没有显示母亲或父亲的极低频场曝露与有害的人类生育结果之间有关联。有一些流产风险增长与母亲磁场曝露之间有关联的证据，但这种证据是不足的。

在几个哺乳动物样本中对高达 150kV/m 极低频电场的曝露进行过评估，包括大组群和连续几代曝露的研究。结果一致显示，没有对生长产生有害影响。

哺乳动物对高达 20mT 极低频磁场的曝露，没有产生外部的、内脏的和骨骼的畸变。一些研究显示出大鼠和小鼠均有轻度骨骼异常的增加。骨骼变化在畸形研究中是较常见的，通常被认为是没有生物意义的。但是，不能排除磁场对骨骼生长微妙的影响。描述生育影响的研究极少有发布，而且从中也不能得出什么结论。

一些关于非哺乳动物的实验对象（例如鸡胚胎、鱼、海胆和昆虫）的研究结果显示，几个微特斯拉水平的极低频磁场，可能会干扰早期生长。但是，在生长毒性总体评估中，与相应的哺乳动物研究相比，非哺乳动物实验对象中的发现占有较轻的权重。

总之，关于生长和生育影响的证据是不足的。

1.10 癌症

国际肿瘤研究机构（IARC）将极低频磁场归类为“怀疑对人类致癌的”（IARC，2002），主要根据2001年及其之前的所有可用数据。本EHC专著对文献的复核，主要针对IARC进行复核之后公布的研究。

1.10.1 流行病学

IARC的分类，很大程度上受到关于儿童期白血病的流行病学研究中所观察到的关联的影响。这种证据被分类为“有限的”，在增加了2002年后发表的另两例儿童期白血病研究，也未改变这种分类。自IARC专著出版后，其他儿童癌症的证据仍是不足的。

IARC专著出版后，发表了许多关于成人女性乳癌风险与极低频磁场曝露关联的报告。这些研究比先前进行的研究规模更大，更不受偏倚影响，所有的结果是阴性的。根据这些研究，有关极低频磁场曝露和女性乳癌风险关联性的证据被大幅削弱了，而且不支持这类关联。

在成人脑癌和白血病方面，IARC专著之后发布的新研究未改变原先的结论，即关于极低频磁场和这些疾病风险之间关联的总体证据是不足的。

对其他疾病和所有其他癌症来说，证据仍是不足的。

1.10.2 实验室动物研究

当前没有最普通形式的儿童期白血病（急性淋巴细胞白血病）足够的动物模型。三种独立的大规模大鼠研究，未提供极低频磁场对自生乳房肿瘤发生率影响的证据。大部分研究报告了极低频磁场不影响啮齿动物模型的白血病或淋巴瘤。一些关于啮齿动物的大规模、长期研究，未显示包括造血、乳腺、脑部和皮肤肿瘤在内的任何种类癌症有任何一致性的增加。

大量研究检查了极低频磁场对大鼠化学诱导乳房肿瘤的影响，得到的结果是不一致的，可能全部或部分是因为实验方案的不同，例如使用了特殊的亚族。大多数关于极低频磁场曝露对化学诱导或辐射诱导白血病/淋巴瘤模型的研究是阴性的。对肝癌前期病变、化学诱导皮肤肿瘤和脑瘤的研究，大部分都报告阴性结果。一项研究称极低频磁场曝露会加快紫外（UV）诱导皮肤肿瘤的发生。

两个研究小组报告，在生物体内极低频磁场曝露后，脑组织内DNA键断裂的水平有所增加。但是，其他研究小组利用各种不同啮齿动物基因毒性模型进行研究后，未发现基因毒性影响的证据。有关调查非基因毒性对癌症影响的研

究结果，是没有结论的。

总之，没有极低频磁场曝露单独会导致癌症的证据。有关极低频磁场曝露与致癌物质结合会促进肿瘤生长的证据，是不足的。

1. 10. 3　体外研究

一般来说，关于细胞极低频场曝露的影响的研究，在低于 50mT 的场中显示不会引起基因毒性。令人注意的例外是，最近有研究报道了场强低至 35μT 时 DNA 损害的证据。但是，这些研究现在还处于评估中，而且我们对这些发现的理解是不完全的。另外，也有增多的证据显示，极低频磁场可能与损害 DNA 的物剂相互作用。

没有清晰的证据表明，极低频磁场会激活与细胞循环控制有关的基因。但是，分析整个基因组反应的系统研究还未进行。

许多其他的细胞研究，例如关于细胞繁殖、凋亡、钙化信号和恶性转化，产生的都是不一致或没有结论的结果。

1. 10. 4　总体结论

自 2002 年 IARC 专著后发布的新的人类、动物和体外研究，未改变极低频磁场作为一种怀疑对人类致癌的总体分类。

1. 11　健康风险评价

根据 WHO 宪章，健康是身体、心理和社交的良好状态，不仅仅是没生病或体弱。风险评价是对健康或环境后果评估信息进行结构性审核的一种概念性框架。健康风险评价可作为风险管理的原始数据，而风险管理包括所有用于制定决策、确定对某曝露是否需要采取特殊行动以及如何采取行动所需的所有活动。

在人类健康风险评估中，只要有可用的人类数据，一般都能比动物数据提供更多信息。动物和体外研究可为人类研究得出的证据提供支持，填补人类研究得出的证据中的数据空白，或在人类研究不足或空缺时做出风险决策。

所有的研究，无论是阳性还是阴性，都需根据它们自身的价值进行评估和判断，然后集合在一起用证据权重法进行处理。重要的是判断一套证据能从多大程度上改变曝露所致后果的可能性。如果不同类型研究（流行病学和实验室）都指向同一结论，而且/或者同类型的多项研究显示出同样的结果时，这种影响的证据通常就被加强了。

1.11.1 急性影响

对频率为 100kHz 及以下的、可能对健康产生有害影响的极低频电场和磁场曝露，其急性生物影响已经确定了。因此，需要制定曝露限值。现有的国际导则已经处理了这个问题。遵循这些导则，可对急性影响提供足够的保护。

1.11.2 慢性影响

科学证据提示的每天、长期的低强度（高于 0.3 ~ 0.4μT）工频磁场曝露引起的健康风险，是根据流行病学研究显示的儿童期白血病风险增加的一致性模式而得出的。危险性评估中的不确定性包括控制选择性偏倚和曝露分类不当的因素，这些因素可能存在于观察到的磁场和儿童期白血病之间的关系之中。另外，事实上，所有的实验室证据和机制证据都不能支持低水平极低频磁场与生物功能或疾病状态变化之间的关系。因此，总体权衡，证据没有强到足以认为是因果性的，但是足以认为应保持关注。

尽管磁场曝露和儿童期白血病之间不能建立因果关系，但是为了给制定政策提供潜在有用的定量估计，在假定这种因果关系存在的前提下，计算了可能产生的公众健康影响。但是，这些计算在很大程度上依赖于曝露分布和其他假设，因此非常不精确。假定这种关联是因果性的，那么估计全球可能因曝露而导致的儿童期白血病病例的数量约为每年 100 ~2400 例。但是，这仅代表了每年白血病总发病例（2000 年全球约为 49000 例）的 0.2% ~4.9%。因此，从全球的角度看，即使存在对公众健康的影响，那这种影响也是有限和不确定的。

人们也研究了许多其他疾病与极低频磁场曝露的可能的关联，包括儿童和成人癌症、抑郁症、自杀、生育功能障碍、发育障碍、免疫系统变异和神经疾病。支持极低频磁场和任何这些疾病关联的科学证据要比儿童期白血病的弱得多，在有些病例研究中（如心血管紊乱或乳癌），有足够的证据表明磁场不会导致疾病。

1.12 保护措施

执行曝露限值以预防极低频电场和磁场曝露已确定的有害影响，是最重要的。这些曝露限值应在对所有相关科学证据进行彻底检查的基础上制定。

至今已确定了的只是急性影响，有两个国际曝露限值导则（ICNIRP，1998；IEEE，2002）可用于防护这类影响。

除了这些确定的急性影响以外，由于极低频磁场曝露与儿童期白血病之间

只存在有限证据，有关长期影响的存在也有不确定性。因此，采取一些预防措施是有道理的。但是，不建议以预防的名义将曝露导则中的限值降低到某任意的水平。这种做法破坏了限值所依据的科学基础，很可能是一种昂贵的、提供不是必然有效的保护的方法。

采取其他一些适当的预防措施来减少曝露是合理和正当的。但是，电力带来了显著的健康、社会和经济利益，预防措施不应损害这些利益。另外，考虑到极低频磁场曝露和儿童期白血病之间关联证据是弱的，以及即使存在这种关联，其对公众健康影响也是有限的，减少曝露给健康带来的利益是不明确的。因此，预防措施的成本应该是非常低的。降低曝露所需的成本会因国家而不同，因此很难给出在成本和电磁场潜在风险之间获得平衡的一般建议。

综上所述，给出以下建议：

- 政策制定者应当为公众和工人制定极低频场曝露导则，导则中规定的曝露水平和科学评估原则最好依据国际导则。
- 政策制定者应建立极低频电磁场防护计划，其中包括对来自所有场源的测量，以确保不超过公众或工人的曝露限值。
- 在保证电力带来的健康、社会和经济利益不受损害的条件下，采取非常低成本的预防措施来减少曝露是合理和正当的。
- 政策制定者、社区规划者和制造商在建造新设施和设计新设备（包括用电设施）时，应采取非常低成本的措施。
- 如果改变工程实践可同时获得其他额外效益，例如更加安全或很少甚至无成本时，应考虑改变工程实践以减少来自设备或装置的极低频曝露。
- 在打算改造现有极低频源时，极低频场的降低应与安全性、可靠性和经济性一并考虑。
- 当建造新设施或对现有设施进行重新布线时，当地政府机构应在保证安全的同时，加强布线管理来减少无意识的接地电流。验证布线中违章或存在问题的预防措施是昂贵的，而且不太可能证明为有效的。
- 国家政府机构应采取有效和公开的沟通策略，使所有利益相关者能够实现知情决断。这包括个人如何减少其自身曝露的信息。
- 当地政府应改善产生极低频电磁场的设备的规划，包括在为极低频电磁场源定点时，加强企业、当地政府和市民之间的咨询。

- 政府和企业应促进研究项目，以减少极低频场曝露健康影响方面科学证据的不确定性。

2 研究建议

识别在极低频场曝露可能的健康影响方面的知识缺陷，是健康风险评价中必不可少的部分。通过识别形成了下列进一步研究的建议（见表 1）。

作为一项总体需求，考虑到中频（IF，常认为是 300Hz ~ 100kHz 的频率）领域中数据缺乏，需要对该频率范围进一步研究。对该频率范围进行健康风险评价所需的知识基础积累得还很少，而且大多数现有研究得出的结果不相一致，故需要进一步核实。构建健康风险评估的充足的中频数据库，通常应包括曝露评价、流行病学、人类实验室研究，以及动物和细胞（体外）研究（ICNIRP，2003；ICNIRP，2004；Litvak，Foster & Repacholi，2002）。

对所有的志愿者研究，必须遵循以人类为对象的研究须完全按伦理原则进行的规则，包括《赫尔辛基宣言》（WMO，2004）中的规定。

对实验室研究，应优先考虑已报道的以下各种反应：① 对这些反应至少已经有一些重复的或确认的证据；② 这些反应与致癌性潜在相关（例如基因毒性）；③ 这些反应足够强，以致可考虑进行机制分析；④ 这些反应在哺乳动物和人的系统中出现。

2.1 源、测量和曝露

进一步辨别不同国家中高极低频曝露住宅的特征，以识别内部和外部源的相对贡献，布线/接地方式的影响，以及可为流行病学评估工作中识别相关曝露度量提供依据的住宅的其他特征。其中重要的一项是要更好地理解胎儿和儿童期的极低频场曝露，特别是来自居所地板下电加热装置的曝露，以及来自住宅楼中变压器的曝露。

有人怀疑在一些环境下职业曝露可能超过现有极低频导则限值。需要更多与从事工作有关的曝露（包括非工频曝露）信息，例如带电维修、在磁共振成像（MRI）磁体腔中或近处（此时曝露在梯形投切的极低频场中）的工作，以及运输系统的工作。同样，还需要关于曝露值可能接近导则限值的公众曝露的

附加知识，包括诸如保安系统、图书馆消磁系统、感应烹饪和水加热装置等场源的知识。

接触电流曝露被假设为是对极低频磁场与儿童期白血病关联的一种可能的解释，除了美国，还需要其他国家进行研究，评估居所电气接地和电气管道方式在增加住宅中接触电流方面有多大作用。在极低频和儿童期白血病方面取得了重要流行病学结果的国家，应优先进行这类研究。

2.2　剂量测定

在过去，大部分实验室研究都将人体内的感应电流作为基本度量，因此剂量测定都集中在这一量上。直到最近，才开始探究外部曝露和感应电场之间的关系。要更好地理解生物影响，需要更多在不同曝露条件下内部电场的数据。

鉴于外部电场和磁场在不同组态下的组合影响，应开展内部电场计算。电场和磁场的异相矢量迭加和空间各不相同的分布，是评估是否符合基本限值所必需的。

几乎没有开展过用合适的解剖学建模对怀孕女性和胎儿的复杂模型进行计算。重要的是评估胎儿中可能增强的感应电场同儿童期白血病之间的关系，同时母亲的职业和居所曝露也都是有关的。

需要进一步优化微观剂量学模型，以考虑那些确认为对感应电场影响更敏感的神经网络和其他复杂亚器官系统的细胞结构。这种建模过程也需要考虑对细胞膜电势的影响，以及对神经传递质释放的影响。

2.3　生物物理机制

目前在机制理解方面存在有明显局限性的三个重要领域是：基团配对机制、人体中的磁性粒子，以及多细胞系统（例如神经元网络）中的信噪比。

基团配对机制是看来最合理的低水平作用机制之一，但是还未发现它在细胞新陈代谢和功能中能成为产生显著影响的媒介。特别重要的是要了解能使这种机制产生作用的曝露低限，以便判断它是否是与致癌性相关的机制。如果在最近的研究中，处于极低频场曝露中的免疫细胞的反应性氧核素有所增加，建议把免疫系统中作为免疫反应产生反应氧核素的细胞作为细胞模型，用以调查基团配对机制的可能性。

根据现有证据，尽管人脑中磁性粒子（磁铁矿晶体）的存在，不能表现出

对环境中的极低频磁场具有敏感性，但是应进一步在理论和实验方面探索在某些条件下这种敏感性是否会存在。此外，还应继续研究上述磁铁物质的存在是否可能对基团配对机制进行修正。

应进一步研究在人脑中作用并提高信噪比的多细胞机制的作用程度，以建立一套对其进行定量的理论框架或确定在这方面的限值。还应使用体外实验方式，进一步研究脑中海马状突起部分和其他部分中的神经元网络的阈值和频率响应。

2.4　神经行为

建议使用协调一致的方案，开展可能对睡眠和完成智力要求较高任务产生影响的实验室志愿者研究。需要验证在比先前使用的更高的磁通密度下，和较宽的频率范围（例如千赫兹范围）的剂量—反应关系。

成人志愿者和动物研究提示，短期曝露于强电场或磁场，可能会引起急性的感知影响。对于制定曝露导则来说，对这种影响的特性描述是很重要的，但是，还缺少在儿童中场影响的专门数据。建议开展基于实验室的有关人类曝露于极低频场时认知和脑电图（EEG）变化的研究，包括儿童和经常处于职业曝露的成人。

对年幼动物活动的研究，提供了对儿童可能的认知影响的有用参考。应研究出生前后极低频磁场曝露对神经系统和认知功能发育的可能影响。使用脑切片或培养神经元研究极低频磁场曝露和感应电场对神经细胞生长的影响，可能是前述研究有益的补充。

需要进一步研究动物实验数据提示的 Opioid（译注：一种主要存在于人体中枢神经系统内的类似吗啡作用的化学物质）和胆碱能反应的潜在健康后果。应进一步开展有关检验动物 Opioid 和胆碱能反应调节的研究，并确定产生这些活动反应的曝露参数和生物学基础。

2.5　神经内分泌系统

现有神经内分泌反应的数据库显示，极低频曝露对人类健康不具有有害影响，因此，没有提出新的研究建议。

2.6　神经变性疾病

一些研究观察到“电力职业”中肌萎缩性（脊髓）侧索硬化风险有所增长。重要的是要进一步研究这种关联，以弄清楚极低频磁场曝露是否与导致这种罕见的神经变性疾病有关。该研究需要进行大规模的队列研究（一种病因学研究方法），需要关于极低频磁场曝露、电击曝露以及其他潜在风险因素的信息。

对于极低频场是否是阿尔茨海默病的风险因素，仍是一个疑问。目前可用的数据不足，这种关联需要进一步研究。特别重要的是，要使用发病率数据，而不是死亡率数据。

2.7　心血管紊乱

关于极低频磁场和心血管疾病风险相关性的进一步研究，可不作优先考虑。

2.8　免疫学和血液病学

曝露到极低频磁场的成人，在免疫和血液参数方面观察到的变化是不一致的。基本上也没有关于儿童的可用研究数据。因此，建议进行关于极低频曝露对年幼动物免疫和血液系统生长影响的研究。

2.9　生育和生长

有一些关于流产风险增长与极低频磁场曝露有关联的证据。考虑到这种关联潜在的高公众健康影响，建议进行进一步流行病学研究。

2.10　癌症

解决流行病学数据（显示极低频磁场曝露和儿童期白血病风险增长之间的关联）和实验及机制数据（不支持这种关联）之间的矛盾，是这一领域中优先级最高的研究。建议流行病学和实验专家们就此进行共同研究。要使新的流行病学研究能提供有益信息，重点必须集中在有关曝露的新视点上，如与其他因素的潜在相互作用，或针对高曝露组群等，否则就只有研究领域的创新了。另外，建议通过附加最近研究的数据，以及在分析中应用新的视点，来改进现有的集合分析。

儿童脑癌研究显示了不一致的结果。同儿童期白血病一样，儿童脑癌研究

的集合分析应能提供很有益的信息，因而建议开展。这类集合分析能低成本地对现有数据，包括产生选择偏倚的可能性，提供更深和更强的洞察，而且如果研究是高度一致的，就能对风险做出最好的估计。

对于成人乳癌，更多最近的研究令人信服地显示与极低频磁场曝露没有关联。因此，关于这种关联的进一步研究处于很低的优先级。

对于成人白血病和脑癌，建议改进现有职业曝露个体的大规模队列研究。关于白血病和脑癌的职业研究（集合分析和荟萃分析）的结果都是不一致和没有结论的。但是，鉴于新数据已经发布了，应该用以更新这些分析。

应通过建立适当的、能反应低水平极低频磁场的、而且可以在实验室间转移的体外和动物模型，为流行病学证据提供辅证，这是优先的。

应建立儿童期白血病的转基因啮齿动物模型，以提供适当的实验动物模型来研究极低频磁场曝露影响。不这样的话，以现有动物研究的证据来权衡，极低频磁场单独作用是没有致癌性的。为此，应高度优先地进行把极低频磁场严格地作为协同致癌物进行评估的体外和动物研究。

关于其他体外研究，应对报导间歇性极低频磁场曝露有基因毒性影响的实验进行重复性核对。

2.11 预防措施

建议在具有科学不确定性领域中，进行制定健康保护政策和政策执行方面的研究，特别是关于“预防”的使用、“预防”的解释，以及对极低频磁场和其他归类为“怀疑对人类致癌”的物质采取预防性措施的影响的评估。只要某物剂对社会形成的潜在健康风险存在不确定性，预防措施对确保公众和工人的适当保护是有正当理由的。在极低频磁场这个问题上已完成的研究很有限，又由于它的重要性，更多的研究是需要的。这可帮助国家将预防与其健康保护政策相结合。

建议进一步开展特别受关注的关于电磁场的风险感受和沟通方面的研究。总体上，已广泛研究了影响风险感受的心理学和社会学因素，但是，关于分析这些因素在电磁场条件下的相对重要性以及识别其他对电磁场来说特殊的因素，所进行的研究还是有限的。最近的研究显示，带有暗示风险信息的预防措施，会改变风险感受，表现为增加或是减少担心。在这方面进行更深入的研究是应

当的。

应对极低频磁场缓解措施开展成本—效益/成本—效果分析。使用成本—效益和成本—效果分析方法评估一项政策是否有益于社会，已经在许多公众政策领域研究过了。有必要制定一个框架，来确定为了完成对极低频磁场的分析，哪些项是需要的。鉴于评估中的不确定性，需要将可定量的和不可定量的项结合考虑。

表 1　　进一步研究建议

课　　题	优先级
源、测量和曝露	
进一步鉴别不同国家高极低频磁场曝露居所的特性	中等
验证职业极低频曝露的知识缺陷，例如在磁共振成像（MRI）中	高
评估美国以外国家中居所布线对儿童感应接触电流的影响大小	中等
剂量测定	
外部电场和磁场对体内电场计算剂量学关系的进一步研究计算，特别是曝露涉及不同方位的组合电场和磁场	中等
怀孕妇女中和胎儿中感应电场和电流的计算	中等
进一步优化考虑神经网络和其他复杂亚器官系统细胞结构的微观剂量模型	中等
生物物理机制	
进一步研究产生反应性氧核素作为其表型功能的免疫细胞的基团配对机制	中等
关于磁铁物在极低频磁场敏感性中可能作用的进一步理论和实验研究	低
使用理论和体外实验，确定多细胞系统（例如神经网络）对由极低频感应的内部电场反应的阈值	高
神经行为	
在很宽的极低频范围内，高磁通密度下，志愿者（包括儿童和职业曝露）的感知、睡眠和脑电图（EEG）研究	中等
研究出生前后曝露对动物感知功能的影响	中等
进一步研究动物中 Opioid 和胆碱能反应	低
神经变性疾病	
进一步研究“电”职业中肌萎缩性（脊髓）侧索硬化疾病的风险及该疾病与极低频磁场曝露的关系；研究阿尔茨海默病与极低频磁场曝露之间的关系	高
免疫学和血液病学	
研究极低频磁场曝露对年幼动物免疫和血液系统生长的后果	低

续表

课　　题	优先级
生育和生长	
进一步研究流产和极低频磁场曝露之间可能的关联	低
癌症	
利用新信息改进现有关于儿童期白血病的集合分析	高
对现有儿童期脑肿瘤研究进行集合分析	高
改进现有对成人白血病、脑部肿瘤研究以及职业曝露个体群队列的集合分析和荟萃分析	中等
建立儿童期白血病的转基因啮齿动物模型，用于极低频研究	高
使用体外和动物研究来评估协同致癌效果	高
体外基因毒性研究的复现	中等
预防措施	
在科学不确定性的领域中，制定健康保护政策和政策执行方面的研究	中等
电磁场风险感受和交流方面的进一步研究	中等
对极低频场缓解措施提出成本—效益/成本—效果分析	中等

ASSESSMENT CONCLUSIONS AND SUGGESTIONS OF WHO'S INTERNATIONAL EMF PROJECT

World Health Organization

CONTENTS

ELECTROMAGNETIC FIELDS AND PUBLIC HEALTH: EXPOSURE TO EXTREMELY LOW FREQUENCY FIELDS (Fact Sheet No. 322, June 2007)

The use of electricity has become an integral part of everyday life. Whenever electricity flows, both electric and magnetic fields exist close to the lines that carry electricity, and close to appliances. Since the late 1970s, questions have been raised whether exposure to these extremely low frequency (ELF) electric and magnetic fields (EMF) produces adverse health consequences. Since then, much research has been done, successfully resolving important issues and narrowing the focus of future research.

In 1996, the World Health Organization (WHO) established the International Electromagnetic Fields Project to investigate potential health risks associated with technologies emitting EMF. A WHO Task Group recently concluded a review of the health implications of ELF fields (WHO, 2007).

This Fact Sheet is based on the findings of that Task Group and updates recent reviews on the health effects of ELF EMF published in 2002 by the International Agency for Research on Cancer (IARC), established under the auspices of WHO, and by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 2003.

1. ELF FIELD SOURCES AND RESIDENTIAL EXPOSURES

Electric and magnetic fields exist wherever electric current flows-in power lines and cables, residential wiring and electrical appliances. Electric fields arise from electric charges, are measured in volts per metre (V/m) and are shielded by common materials, such as wood and metal. Magnetic fields arise from the motion of electric

charges (i. e. a current), are expressed in tesla (T), or more commonly in millitesla (mT) or microtesla (μT). In some countries another unit called the gauss (G), is commonly used (10000G = 1T). These fields are not shielded by most common materials, and pass easily through them. Both types of fields are strongest close to the source and diminish with distance.

Most electric power operates at a frequency of 50 or 60 cycles per second, or hertz (Hz). Close to certain appliances, the magnetic field values can be of the order of a few hundred microtesla. Underneath power lines, magnetic fields can be about 20μT and electric fields can be several thousand volts per metre. However, average residential power-frequency magnetic fields in homes are much lower-about 0.07μT in Europe and 0.11μT in North America. Mean values of the electric field in the home are up to several tens of volts per metre.

2. TASK GROUP EVALUATION

In October 2005, WHO convened a Task Group of scientific experts to assess any risks to health that might exist from exposure to ELF electric and magnetic fields in the frequency range >0 to 100000Hz (100kHz). While IARC examined the evidence regarding cancer in 2002, this Task Group reviewed evidence for a number of health effects, and updated the evidence regarding cancer. The conclusions and recommendations of the Task Group are presented in a WHO Environmental Health Criteria (EHC) monograph (WHO, 2007).

Following a standard health risk assessment process, the Task Group concluded that there are no substantive health issues related to ELF electric fields at levels generally encountered by members of the public. Thus the remainder of this fact sheet addresses predominantly the effects of exposure to ELF magnetic fields.

3. SHORT-TERM EFFECTS

There are established biological effects from acute exposure at high levels (well

above 100μT) that are explained by recognized biophysical mechanisms. External ELF magnetic fields induce electric fields and currents in the body which, at very high field strengths, cause nerve and muscle stimulation and changes in nerve cell excitability in the central nervous system.

4. POTENTIAL LONG-TERM EFFECTS

Much of the scientific research examining long-term risks from ELF magnetic field exposure has focused on childhood leukaemia. In 2002, IARC published a monograph classifying ELF magnetic fields as "possibly carcinogenic to humans". This classification is used to denote an agent for which there is limited evidence of carcinogenicity in humans and less than sufficient evidence for carcinogenicity in experimental animals (other examples include coffee and welding fumes). This classification was based on pooled analyses of epidemiological studies demonstrating a consistent pattern of a two-fold increase in childhood leukaemia associated with average exposure to residential power-frequency magnetic field above 0.3 to 0.4μT. The Task Group concluded that additional studies since then do not alter the status of this classification.

However, the epidemiological evidence is weakened by methodological problems, such as potential selection bias. In addition, there are no accepted biophysical mechanisms that would suggest that low-level exposures are involved in cancer development. Thus, if there were any effects from exposures to these low-level fields, it would have to be through a biological mechanism that is as yet unknown. Additionally, animal studies have been largely negative. Thus, on balance, the evidence related to childhood leukaemia is not strong enough to be considered causal.

Childhood leukaemia is a comparatively rare disease with a total annual number of new cases estimated to be 49000 worldwide in 2000. Average magnetic field exposures above 0.3μT in homes are rare: it is estimated that only between 1% and 4% of children live in such conditions. If the association between magnetic fields and

childhood leukaemia is causal, the number of cases worldwide that might be attributable to magnetic field exposure is estimated to range from 100 to 2400 cases per year, based on values for the year 2000, representing 0.2% to 4.95% of the total incidence for that year. Thus, if ELF magnetic fields actually do increase the risk of the disease, when considered in a global context, the impact on public health of ELF EMF exposure would be limited.

A number of other adverse health effects have been studied for possible association with ELF magnetic field exposure. These include other childhood cancers, cancers in adults, depression, suicide, cardiovascular disorders, reproductive dysfunction, developmental disorders, immunological modifications, neurobehavioural effects and neurodegenerative disease. The WHO Task Group concluded that scientific evidence supporting an association between ELF magnetic field exposure and all of these health effects is much weaker than for childhood leukaemia. In some instances (i.e. for cardiovascular disease or breast cancer) the evidence suggests that these fields do not cause them.

5. INTERNATIONAL EXPOSURE GUIDELINES

Health effects related to short-term, high-level exposure have been established and form the basis of two international exposure limit guidelines (ICNIRP, 1998; IEEE, 2002). At present, these bodies consider the scientific evidence related to possible health effects from long-term, low-level exposure to ELF fields insufficient to justify lowering these quantitative exposure limits.

6. WHO'S GUIDANCE

For high-level short-term exposures to EMF, adverse health effects have been scientifically established (ICNIRP, 2003). International exposure guidelines designed to protect workers and the public from these effects should be adopted by policy makers. EMF protection programs should include exposure measurements from

sources where exposures might be expected to exceed limit values.

Regarding long-term effects, given the weakness of the evidence for a link between exposure to ELF magnetic fields and childhood leukaemia, the benefits of exposure reduction on health are unclear. In view of this situation, the following recommendations are given:

- Government and industry should monitor science and promote research programmes to further reduce the uncertainty of the scientific evidence on the health effects of ELF field exposure. Through the ELF risk assessment process, gaps in knowledge have been identified and these form the basis of a new research agenda.
- Member States are encouraged to establish effective and open communication programmes with all stakeholders to enable informed decision-making. These may include improving coordination and consultation among industry, local government, and citizens in the planning process for ELF EMF-emitting facilities.
- When constructing new facilities and designing new equipment, including appliances, low-cost ways of reducing exposures may be explored. Appropriate exposure reduction measures will vary from one country to another. However, policies based on the adoption of arbitrary low exposure limits are not warranted.

7. FURTHER READING

WHO — World Health Organization. Extremely low frequency fields. Environmental Health Criteria, Vol. 238. Geneva, World Health Organization, 2007.

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Non-ionizing radiation, Part 1: Static and extremely low-frequency (ELF) electric and magnetic fields. Lyon, IARC, 2002 (Monographs on the Evaluation of Carcinogenic Risks to Humans, 80).

ICNIRP — International Commission on Non-Ionizing Radiation Protection.

Exposure to static and low frequency electromagnetic fields, biological effects and health consequences (0 ~ 100kHz). Bernhardt JH et al., eds. Oberschleissheim, International Commission on Non-ionizing Radiation Protection, 2003 (ICNIRP 13/2003).

ICNIRP — International Commission on Non-Ionizing Radiation Protection (1998). Guidelines for limiting exposure to time varying electric, magnetic and electromagnetic fields (up to 300GHz). Health Physics 74(4), 494 – 522.

IEEE Standards Coordinating Committee 28. IEEE standard for safety levels with respect to human exposure to electromagnetic fields, 0 ~ 3kHz. New York, NY, IEEE-The Institute of Electrical and Electronics Engineers, 2002 (IEEE Std. C95.6 – 2002).

EHC238: SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDY

This Environmental Health Criteria (EHC) monograph addresses the possible health effects of exposure to extremely low frequency (ELF) electric and magnetic fields. It reviews the physical characteristics of ELF fields as well as the sources of exposure and measurement. However, its main objectives are to review the scientific literature on the biological effects of exposure to ELF fields in order to assess any health risks from exposure to these fields and to use this health risk assessment to make commendations to national authorities on health protection programs.

The frequencies under consideration range from above 0Hz to 100kHz. By far the majority of studies have been conducted on power-frequency (50 or 60Hz) magnetic fields, with a few studies using power-frequency electric fields. In addition, there have been a number of studies concerning very low frequency (VLF, 3 ~ 30kHz) fields, switched gradient magnetic fields used in magnetic resonance imaging, and the weaker VLF fields emitted by visual display units and televisions. This chapter summarizes the main conclusions and recommendations from each section as well as the overall conclusions of the health risk assessment process. The terms used in this monograph to describe the strength of evidence for a given health outcome are as follows. Evidence is termed "limited" when it is restricted to a single study or when there are unresolved questions concerning the design, conduct or interpretation of a number of studies. "Inadequate" evidence is used when the studies cannot be interpreted as showing either the presence or absence of an effect because of major qualitative or quantitative limitations, or when no data are available. Key gaps in knowledge were also identified and the research needed to fill these gaps has been summarized in the section entitled "Recommendations for research".

1 SUMMARY

1.1 SOURCES, MEASUREMENTS AND EXPOSURES

Electric and magnetic fields exist wherever electricity is generated, transmitted or distributed in power lines or cables, or used in electrical appliances. Since the use of electricity is an integral part of our modern lifestyle, these fields are ubiquitous in our environment.

The unit of electric field strength is volts per metre (Vm^{-1}) or kilovolts per metre (kVm^{-1}) and for magnetic fields the flux density is measured in tesla (T), or more commonly in millitesla (mT) or microtesla (μT) is used.

Residential exposure to power-frequency magnetic fields does not vary dramatically across the world. The geometric-mean magnetic field in homes ranges between 0.025 and 0.07μT in Europe and 0.055 and 0.11μT in the USA. The mean values of the electric field in the home are in the range of several tens of volts per metre. In the vicinity of certain appliances, the instantaneous magnetic-field values can be as much as a few hundred microtesla. Near power lines, magnetic fields reach approximately 20μT and electric fields up to several thousand volts per metre.

Few children have time-averaged exposures to residential 50 or 60Hz magnetic fields in excess of the levels associated with an increased incidence of childhood leukaemia (see Section 1.10). Approximately 1% to 4% have mean exposures above 0.3μT and only 1% to 2% have median exposures in excess of 0.4μT.

Occupational exposure, although predominantly to power-frequency fields, may also include contributions from other frequencies. The average magnetic field exposures in the workplace have been found to be higher in "electrical occupations" than in other occupations such as office work, ranging from 0.4 ~ 0.6μT for

electricians and electrical engineers to approximately 1.0μT for power line workers, with the highest exposures for welders, railway engine drivers and sewing machine operators (above 3μT). The maximum magnetic field exposures in the workplace can reach approximately 10 mT and this is invariably associated with the presence of conductors carrying high currents. In the electrical supply industry, workers may be exposed to electric fields up to 30kVm^{-1}.

1.2 ELECTRIC AND MAGNETIC FIELDS INSIDE THE BODY

Exposure to external electric and magnetic fields at extremely low frequencies induces electric fields and currents inside the body. Dosimetry describes the relationship between the external fields and the induced electric field and current density in the body, or other parameters associated with exposure to these fields. The locally induced electric field and current density are of particular interest because they relate to the stimulation of excitable tissue such as nerve and muscle.

The bodies of humans and animals significantly perturb the spatial distribution of an ELF electric field. At low frequencies the body is a good conductor and the perturbed field lines outside the body are nearly perpendicular to the body surface. Oscillating charges are induced on the surface of the exposed body and these induce currents inside the body. The key features of dosimetry for the exposure of humans to ELF electric fields are as follows:

- The electric field inside the body is normally five to six orders of magnitude smaller than the external electric field.
- When exposure is mostly to the vertical field, the predominant direction of the induced fields is also vertical.
- For a given external electric field, the strongest induced fields are for the human body in perfect contact through the feet with ground (electrically grounded) and the weakest induced fields are for the body insulated from the ground (in "free space").
- The total current flowing in a body in perfect contact with ground is determined

by the body size and shape (including posture), rather than tissue conductivity.

- The distribution of induced currents across the various organs and tissues is determined by the conductivity of those tissues.
- The distribution of an induced electric field is also affected by the conductivities, but less so than the induced current.
- There is also a separate phenomenon in which the current in the body is produced by means of contact with a conductive object located in an electric field.

For magnetic fields, the permeability of tissue is the same as that of air, so the field in tissue is the same as the external field. The bodies of humans and animals do not significantly perturb the field. The main interaction of magnetic fields is the Faraday induction of electric fields and associated current densities in the conductive tissues. The key features of dosimetry for the exposure of humans to ELF magnetic fields are as follows:

- The induced electric field and current depend on the orientation of the external field. Induced fields in the body as a whole are greatest when the field is aligned from the front to the back of the body, but for some individual organs the highest values are for the field aligned from side to side.
- The weakest electric fields are induced by a magnetic field oriented along the vertical body axis.
- For a given magnetic field strength and orientation, higher electric fields are induced in larger bodies.
- The distribution of the induced electric field is affected by the conductivity of the various organs and tissues. These have a limited effect on the distribution of induced current density.

1.3 BIOPHYSICAL MECHANISMS

Various proposed direct and indirect interaction mechanisms for ELF electric and

magnetic fields are examined for plausibility, in particular whether a "signal" generated in a biological process by exposure to a field can be discriminated from inherent random noise and whether the mechanism challenges scientific principles and current scientific knowledge. Many mechanisms become plausible only at fields above a certain strength. Nevertheless, the lack of identified plausible mechanisms does not rule out the possibility of health effects even at very low field levels, provided basic scientific principles are adhered to.

Of the numerous proposed mechanisms for the direct interaction of fields with the human body, three stand out as potentially operating at lower field levels than the others: induced electric fields in neural networks, radical pairs and magnetite.

Electric fields induced in tissue by exposure to ELF electric or magnetic fields will directly stimulate single myelinated nerve fibres in a biophysically plausible manner when the internal field strength exceeds a few volts per metre. Much weaker fields can affect synaptic transmission in neural networks as opposed to single cells. Such signal processing by nervous systems is commonly used by multicellular organisms to detect weak environmental signals. A lower bound on neural network discrimination of 1mV m^{-1} has been suggested, but based on current evidence, threshold values around 10 ~ 100mV m^{-1} seem to be more likely.

The radical pair mechanism is an accepted way in which magnetic fields can affect specific types of chemical reactions, generally increasing concentrations of reactive free radicals in low fields and decreasing them in high fields. These increases have been seen in magnetic fields of less than 1 mT. There is some evidence linking this mechanism to navigation during bird migration. Both on theoretical grounds and because the changes produced by ELF and static magnetic fields are similar, it is suggested that power-frequency fields of much less than the geomagnetic field of around 50μT are unlikely to be of much biological significance.

Magnetite crystals, small ferromagnetic crystals of various forms of iron oxide, are found in animal and human tissues, although in trace amounts. Like free radicals, they have been linked to orientation and navigation in migratory animals, although the presence of trace quantities of magnetite in the human brain does not confer an ability

to detect the weak geomagnetic field. Calculations based on extreme assumptions suggest a lower bound for the effects on magnetite crystals of ELF fields of 5μT.

Other direct biophysical interactions of fields, such as the breaking of chemical bonds, the forces on charged particles and the various narrow bandwidth "resonance" mechanisms, are not considered to provide plausible explanations for the interactions at field levels encountered in public and occupational environments.

With regard to indirect effects, the surface electric charge induced by electric fields can be perceived, and it can result in painful microshocks when touching a conductive object. Contact currents can occur when young children touch, for example, a tap in the bathtub in some homes. This produces small electric fields, possibly above background noise levels, in bone marrow. However, whether these present a risk to health is unknown.

High-voltage power lines produce clouds of electrically charged ions as a consequence of corona discharge. It is suggested that they could increase the deposition of airborne pollutants on the skin and on airways inside the body, possibly adversely affecting health. However, it seems unlikely that corona ions will have more than a small effect, if any, on long-term health risks, even in the individuals who are most exposed.

None of the three direct mechanisms considered above seem plausible causes of increased disease incidence at the exposure levels generally encountered by people. In fact they only become plausible at levels orders of magnitude higher and indirect mechanisms have not yet been sufficiently investigated. This absence of an identified plausible mechanism does not rule out the possibility of adverse health effects, but it does create a need for stronger evidence from biology and epidemiology.

1.4 NEUROBEHAVIOUR

Exposure to power-frequency electric fields causes well-defined biological responses, ranging from perception to annoyance, through surface electric charge effects. These responses depend on the field strength, the ambient environmental

conditions and individual sensitivity. The thresholds for direct perception by 10% of volunteers varied between 2 and $20kVm^{-1}$, while 5% found 15 ~ $20kVm^{-1}$ annoying. The spark discharge from a person to ground is found to be painful by 7% of volunteers in a field of $5kVm^{-1}$. Thresholds for the discharge from a charged object through a grounded person depend on the size of the object and therefore require specific assessment.

High field strength, rapidly pulsed magnetic fields can stimulate peripheral or central nerve tissue; such effects can arise during magnetic resonance imaging (MRI) procedures, and are used in transcranial magnetic stimulation. Threshold induced electric field strengths for direct nerve stimulation could be as low as a few volts per metre. The threshold is likely to be constant over a frequency range between a few hertz and a few kilohertz. People suffering from or predisposed to epilepsy are likely to be more susceptible to induced ELF electric fields in the central nervous system (CNS). Furthermore, sensitivity to electrical stimulation of the CNS seems likely to be associated with a family history of seizure and the use of tricyclic antidepressants, neuroleptic agents and other drugs that lower the seizure threshold.

The function of the retina, which is a part of the CNS, can be affected by exposure to much weaker ELF magnetic fields than those that cause direct nerve stimulation. A flickering light sensation, called magnetic phosphenes or magnetophosphenes, results from the interaction of the induced electric field with electrically excitable cells in the retina. Threshold induced electric field strengths in the extracellular fluid of the retina have been estimated to lie between about 10 and $100mVm^{-1}$ at 20Hz. There is, however, considerable uncertainty attached to these values.

The evidence for other neurobehavioural effects in volunteer studies, such as the effects on brain electrical activity, cognition, sleep, hypersensitivity and mood, is less clear. Generally, such studies have been carried out at exposure levels below those required to induce the effects described above, and have produced evidence only of subtle and transitory effects at best. The conditions necessary to elicit such responses are not well-defined at present. There is some evidence suggesting the

existence of field-dependent effects on reaction time and on reduced accuracy in the performance of some cognitive tasks, which is supported by the results of studies on the gross electrical activity of the brain. Studies investigating whether magnetic fields affect sleep quality have reported inconsistent results. It is possible that these inconsistencies may be attributable in part to differences in the design of the studies.

Some people claim to be hypersensitive to EMFs in general. However, the evidence from double-blind provocation studies suggests that the reported symptoms are unrelated to EMF exposure.

There is only inconsistent and inconclusive evidence that exposure to ELF electric and magnetic fields causes depressive symptoms or suicide. Thus, the evidence is considered inadequate.

In animals, the possibility that exposure to ELF fields may affect neurobehavioural functions has been explored from a number of perspectives using a range of exposure conditions. Few robust effects have been established. There is convincing evidence that power-frequency electric fields can be detected by animals, most likely as a result of surface charge effects, and may elicit transient arousal or mild stress. In rats, the detection range is between 3 and 13kVm^{-1}. Rodents have been shown to be aversive to field strengths greater than 50kVm^{-1}. Other possible field-dependent changes are less well-defined; laboratory studies have only produced evidence of subtle and transitory effects. There is some evidence that exposure to magnetic fields may modulate the functions of the opioid and cholinergic neurotransmitter systems in the brain, and this is supported by the results of studies investigating the effects on analgesia and on the acquisition and performance of spatial memory tasks.

1.5 NEUROENDOCRINE SYSTEM

The results of volunteer studies as well as residential and occupational epidemiological studies suggest that the neuroendocrine system is not adversely affected by exposure to power-frequency electric or magnetic fields. This applies particularly to the circulating levels of specific hormones of the neuroendocrine

system, including melatonin, released by the pineal gland, and to a number of hormones involved in the control of body metabolism and physiology, released by the pituitary gland. Subtle differences were sometimes observed in the timing of melatonin release associated with certain characteristics of exposure, but these results were not consistent. It is very difficult to eliminate possible confounding by a variety of environmental and lifestyle factors that might also affect hormone levels. Most laboratory studies of the effects of ELF exposure on night-time melatonin levels in volunteers found no effect when care was taken to control possible confounding.

From the large number of animal studies investigating the effects of power-frequency electric and magnetic fields on rat pineal and serum melatonin levels, some reported that exposure resulted in night-time suppression of melatonin. The changes in melatonin levels first observed in early studies of electric field exposures up to $100 kVm^{-1}$ could not be replicated. The findings from a series of more recent studies, which showed that circularlypolarised magnetic fields suppressed night-time melatonin levels, were weakened by inappropriate comparisons between exposed animals and his torical controls. The data from other experiments in rodents, covering intensity levels from a few microtesla to 5 mT, were equivocal, with some results showing depression of melatonin, but others showing no changes. In seasonally breeding animals, the evidence for an effect of exposure to power-frequency fields on melatonin levels and melatonin-dependent reproductive status is predominantly negative. No convincing effect on melatonin levels has been seen in a study of non-human primates chronically exposed to power-frequency fields, although a preliminary study using two animals reported melatonin suppression in response to an irregular and intermittent exposure.

The effects of exposure to ELF fields on melatonin production or release in isolated pineal glands were variable, although relatively few in vitro studies have been undertaken. The evidence that ELF exposure interferes with the action of melatonin on breast cancer cells in vitro is intriguing. However this system suffers from the disadvantage that the cell lines frequently show genotypic and phenotypic drift in culture that can hinder transferability between laboratories.

No consistent effects have been seen in the stress-related hormones of the pituitary-adrenal axis in a variety of mammalian species, with the possible exception of short-lived stress following the onset of ELF electric field exposure at levels high enough to be perceived. Similarly, while few studies have been carried out, mostly negative or inconsistent effects have been observed in the levels of growth hormone and of hormones involved in controlling metabolic activity or associated with the control of reproduction and sexual development.

Overall, these data do not indicate that ELF electric and/or magnetic fields affect the neuroendocrine system in a way that would have an adverse impact on human health and the evidence is thus considered inadequate.

1.6 NEURODEGENERATIVE DISORDERS

It has been hypothesized that exposure to ELF fields is associated with several neurodegenerative diseases. For Parkinson's disease and multiple sclerosis the number of studies has been small and there is no evidence for an association with these diseases. For Alzheimer's disease and amyotrophic lateral sclerosis (ALS) more studies have been published. Some of these reports suggest that people employed in electrical occupations might have an increased risk of ALS. So far, no biological mechanism has been established which can explain this association, although it could have arisen because of confounders related to electrical occupations, such as electric shocks. Overall, the evidence for the association between ELF exposure and ALS is considered to be inadequate.

The few studies investigating the association between ELF exposure and Alzheimer's disease are inconsistent. However, the higher quality studies that focused on Alzheimer morbidity rather than mortality do not indicate an association. Altogether, the evidence for an association between ELF exposure and Alzheimer's disease is inadequate.

1.7 CARDIOVASCULAR DISORDERS

Experimental studies of both short-term and long-term exposure indicate that while electric shock is an obvious health hazard, other hazardous cardiovascular effects associated with ELF fields are unlikely to occur at exposure levels commonly encountered environmentally or occupationally. Although various cardiovascular changes have been reported in the literature, the majority of effects are small and the results have not been consistent within and between studies. With one exception, none of the studies of cardiovascular disease morbidity and mortality has shown an association with exposure. Whether a specific association exists between exposure and altered autonomic control of the heart remains speculative. Overall, the evidence does not support an association between ELF exposure and cardiovascular disease.

1.8 IMMUNOLOGY AND HAEMATOLOGY

Evidence for the effects of ELF electric or magnetic fields on components of the immune system is generally inconsistent. Many of the cell populations and functional markers were unaffected by exposure. However, in some human studies with fields from 10μT to 2 mT, changes were observed in natural killer cells, which showed both increased and decreased cell numbers, and in total white blood cell counts, which showed no change or decreased numbers. In animal studies, reduced natural killer cell activity was seen in female mice, but not in male mice or in rats of either sex. White blood cell counts also showed inconsistency, with decreases or no change reported in different studies. The animal exposures had an even broader range of 2μT to 30 mT. The difficulty in interpreting the potential health impact of these data is due to the large variations in exposure and environmental conditions, the relatively small numbers of subjects tested and the broad range of endpoints.

There have been few studies carried out on the effects of ELF magnetic fields on the haematological system. In experiments evaluating differential white blood cell

counts, exposures ranged from 2μT to 2 mT. No consistent effects of acute exposure to ELF magnetic fields or to combined ELF electric and magnetic fields have been found in either human or animal studies.

Overall therefore, the evidence for effects of ELF electric or magnetic fields on the immune and haematological system is considered inadequate.

1.9 REPRODUCTION AND DEVELOPMENT

On the whole, epidemiological studies have not shown an association between adverse human reproductive outcomes and maternal or paternal exposure to ELF fields. There is some evidence for an increased risk of miscarriage associated with maternal magnetic field exposure, but this evidence is inadequate.

Exposures to ELF electric fields of up to $150 kVm^{-1}$ have been evaluated in several mammalian species, including studies with large group sizes and exposure over several generations. The results consistently show no adverse developmental effects.

The exposure of mammals to ELF magnetic fields of up to 20 mT does not result in gross external, visceral or skeletal malformations. Some studies show an increase in minor skeletal anomalies, in both rats and mice. Skeletal variations are relatively common findings in teratological studies and are often considered biologically insignificant. However, subtle effects of magnetic fields on skeletal development cannot be ruled out. Very few studies have been published which address reproductive effects and no conclusions can be drawn from them.

Several studies on non-mammalian experimental models (chick embryos, fish, sea urchins and insects) have reported findings indicating that ELF magnetic fields at microtesla levels may disturb early development. However, the findings of non-mammalian experimental models carry less weight in the overall evaluation of developmental toxicity than those of corresponding mammalian studies.

Overall, the evidence for developmental and reproductive effects is inadequate.

1.10 CANCER

The IARC classification of ELF magnetic fields as "possibly carcinogenic to humans" (IARC, 2002) is based upon all of the available data prior to and including 2001. The review of literature in this EHC monograph focuses mainly on studies published after the IARC review.

Epidemiology

The IARC classification was heavily influenced by the associations observed in epidemiological studies on childhood leukaemia. The classification of this evidence as limited does not change with the addition of two childhood leukaemia studies published after 2002. Since the publication of the IARC monograph the evidence for other childhood cancers remains inadequate.

Subsequent to the IARC monograph a number of reports have been published concerning the risk of female breast cancer in adults associated with ELF magnetic field exposure. These studies are larger than the previous ones and less susceptible to bias, and overall are negative. With these studies, the evidence for an association between ELF magnetic field exposure and the risk of female breast cancer is weakened considerably and does not support an association of this kind.

In the case of adult brain cancer and leukaemia, the new studies published after the IARC monograph do not change the conclusion that the overall evidence for an association between ELF magnetic fields and the risk of these diseases remains inadequate.

For other diseases and all other cancers, the evidence remains inadequate.

Laboratory animal studies

There is currently no adequate animal model of the most common form of childhood leukaemia, acute lymphoblastic leukaemia. Three independent large-scale studies of rats provided no evidence of an effect of ELF magnetic fields on the incidence of spontaneous mammary tumours. Most studies report no effect of ELF magnetic fields on leukaemia or lymphoma in rodent models. Several large-scale

long-term studies in rodents have not shown any consistent increase in any type of cancer, including haematopoietic, mammary, brain and skin tumours.

A substantial number of studies have examined the effects of ELF magnetic fields on chemically-induced mammary tumours in rats. Inconsistent results were obtained that may be due in whole or in part to differences in experimental protocols, such as the use of specific sub-strains. Most studies on the effects of ELF magnetic field exposure on chemically-induced or radiation-induced leukaemia/lymphoma models were negative. Studies of pre-neoplastic liver lesions, chemically-induced skin tumours and brain tumours reported predominantly negative results. One study reported an acceleration of UV-induced skin tumourigenesis upon exposure to ELF magnetic fields.

Two groups have reported increased levels of DNA strand breaks in brain tissue following in vivo exposure to ELF magnetic fields. However, other groups, using a variety of different rodent genotoxicity models, found no evidence of genotoxic effects. The results of studies investigating nongenotoxic effects relevant to cancer are inconclusive.

Overall there is no evidence that exposure to ELF magnetic fields alone causes tumours. The evidence that ELF magnetic field exposure can enhance tumour development in combination with carcinogens is inadequate.

In vitro studies

Generally, studies of the effects of ELF field exposure of cells have shown no induction of genotoxicity at fields below 50 mT. The notable exception is evidence from recent studies reporting DNA damage at field strengths as low as 35 μT; however, these studies are still being evaluated and our understanding of these findings is incomplete. There is also increasing evidence that ELF magnetic fields may interact with DNA-damaging agents.

There is no clear evidence of the activation by ELF magnetic fields of genes associated with the control of the cell cycle. However, systematic studies analysing the response of the whole genome have yet to be performed.

Many other cellular studies, for example on cell proliferation, apoptosis,

calcium signalling and malignant transformation, have produced inconsistent or inconclusive results.

Overall conclusion

New human, animal and in vitro studies, published since the 2002 IARC monograph, do not change the overall classification of ELF magnetic fields as a possible human carcinogen.

1.11 HEALTH RISK ASSESSMENT

According to the WHO Constitution, health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. A risk assessment is a conceptual framework for a structured review of information relevant to estimating health or environmental outcomes. The health risk assessment can be used as an input to risk management that encompasses all the activities needed to reach decisions on whether an exposure requires any specific action(s) and the undertaking of these actions.

In the evaluation of human health risks, sound human data, whenever available, are generally more informative than animal data. Animal and in vitro studies can support evidence from human studies, fill data gaps left in the evidence from human studies or be used to make a decision about risks when human studies are inadequate or absent.

All studies, with either positive or negative effects, need to be evaluated and judged on their own merit and then all together in a weight-of-evidence approach. It is important to determine to what extent a set of evidence changes the probability that exposure causes an outcome. The evidence for an effect is generally strengthened if the results from different types of studies (epidemiology and laboratory) point to the same conclusion and/or when multiple studies of the same type show the same result.

Acute effects

Acute biological effects have been established for exposure to ELF electric and magnetic fields in the frequency range up to 100kHz that may have adverse

consequences on health. Therefore, exposure limits are needed. International guidelines exist that have addressed this issue. Compliance with these guidelines provides adequate protection for acute effects.

Chronic effects

Scientific evidence suggesting that everyday, chronic low-intensity (above 0.3 ~ 0.4μT) power-frequency magnetic field exposure poses a health risk is based on epidemiological studies demonstrating a consistent pattern of increased risk for childhood leukaemia. Uncertainties in the hazard assessment include the role that control selection bias and exposure misclassification might have on the observed relationship between magnetic fields and childhood leukaemia. In addition, virtually all of the laboratory evidence and the mechanistic evidence fail to support a relationship between low-level ELF magnetic fields and changes in biological function or disease status. Thus, on balance, the evidence is not strong enough to be considered causal, but sufficiently strong to remain a concern.

Although a causal relationship between magnetic field exposure and childhood leukaemia has not been established, the possible public health impact has been calculated assuming causality in order to provide a potentially useful input into policy. However, these calculations are highly dependent on the exposure distributions and other assumptions, and are therefore very imprecise. Assuming that the association is causal, the number of cases of childhood leukaemia worldwide that might be attributable to exposure can be estimated to range from 100 to 2400 cases per year. However, this represents 0.2 to 4.9% of the total annual incidence of leukaemia cases, estimated to be 49000 worldwide in 2000. Thus, in a global context, the impact on public health, if any, would be limited and uncertain.

A number of other diseases have been investigated for possible association with ELF magnetic field exposure. These include cancers in both children and adults, depression, suicide, reproductive dysfunction, developmental disorders, immunological modifications and neurological disease. The scientific evidence supporting a linkage between ELF magnetic fields and any of these diseases is much weaker than for childhood leukaemia and in some cases (for example, for cardiovascular disease or

breast cancer) the evidence is sufficient to give confidence that magnetic fields do not cause the disease.

1.12 PROTECTIVE MEASURES

It is essential that exposure limits be implemented in order to protect against the established adverse effects of exposure to ELF electric and magnetic fields. These exposure limits should be based on a thorough examination of all the relevant scientific evidence.

Only the acute effects have been established and there are two international exposure limit guidelines (ICNIRP, 1998; IEEE, 2002) designed to protect against these effects.

As well as these established acute effects, there are uncertainties about the existence of chronic effects, because of the limited evidence for a link between exposure to ELF magnetic fields and childhood leukaemia. Therefore the use of precautionary approaches is warranted. However, it is not recommended that the limit values in exposure guidelines be reduced to some arbitrary level in the name of precaution. Such practice undermines the scientific foundation on which the limits are based and is likely to be an expensive and not necessarily effective way of providing protection.

Implementing other suitable precautionary procedures to reduce exposure is reasonable and warranted. However, electric power brings obvious health, social and economic benefits, and precautionary approaches should not compromise these benefits. Furthermore, given both the weakness of the evidence for a link between exposure to ELF magnetic fields and childhood leukaemia, and the limited impact on public health if there is a link, the benefits of exposure reduction on health are unclear. Thus the costs of precautionary measures should be very low. The costs of implementing exposure reductions will vary from one country to another, making it very difficult to provide a general recommendation for balancing the costs against the potential risk from ELF fields.

In view of the above, the following recommendations are given.

- Policy-makers should establish guidelines for ELF field exposure for both the general public and workers. The best source of guidance for both exposure levels and the principles of scientific review are the international guidelines.
- Policy-makers should establish an ELF EMF protection programme that includes measurements of fields from all sources to ensure that the exposure limits are not exceeded either for the general public or workers.
- Provided that the health, social and economic benefits of electric power are not compromised, implementing very low-cost precautionary procedures to reduce exposure is reasonable and warranted.
- Policy-makers, community planners and manufacturers should implement very low-cost measures when constructing new facilities and designing new equipment including appliances.
- Changes to engineering practice to reduce ELF exposure from equipment or devices should be considered, provided that they yield other additional benefits, such as greater safety, or little or no cost.
- When changes to existing ELF sources are contemplated, ELF field reduction should be considered alongside safety, reliability and economic aspects.
- Local authorities should enforce wiring regulations to reduce unintentional ground currents when building new or rewiring existing facilities, while maintaining safety. Proactive measures to identify violations or existing problems in wiring would be expensive and unlikely to be justified.
- National authorities should implement an effective and open communication strategy to enable informed decision-making by all stakeholders; this should include information on how individuals can reduce their own exposure.
- Local authorities should improve planning of ELF EMF-emitting facilities, including better consultation between industry, local government, and citizens when siting major ELF EMF-emitting sources.
- Government and industry should promote research programmes to reduce the uncertainty of the scientific evidence on the health effects of ELF field exposure.

2

RECOMMENDATIONS FOR RESEARCH

Identifying the gaps in the knowledge concerning the possible health effects of exposure to ELF fields is an essential part of this health risk assessment. This has resulted in the following recommendations for further research (summarized in Table 1).

As an overarching need, further research on intermediate frequencies (IF), usually taken as frequencies between 300Hz and 100kHz, is required, given the present lack of data in this area. Very little of the required knowledge base for a health risk assessment has been gathered and most existing studies have contributed inconsistent results, which need to be further substantiated. General requirements for constituting a sufficient IF database for health risk assessment include exposure assessment, epidemiological and human laboratory studies, and animal and cellular (in vitro) studies (ICNIRP, 2003; ICNIRP, 2004; Litvak, Foster & Repacholi, 2002).

For all volunteer studies, it is mandatory that research on human subjects is conducted in full accord with ethical principles, including the provisions of the Helsinki Declaration (WMO, 2004).

For laboratory studies, priority should be given to reported responses (i) for which there is at least some evidence of replication or confirmation, (ii) that are potentially relevant to carcinogenesis (for example, genotoxicity), (iii) that are strong enough to allow mechanistic analysis and (iv) that occur in mammalian or human systems.

2.1 SOURCES, MEASUREMENTS AND EXPOSURES

The further characterization of homes with high ELF exposure in different

countries to identify relative contributions of internal and external sources, the influence of wiring/grounding practices and other characteristics of the home could give insights into identifying a relevant exposure metric for epidemiological assessment. An important component of this is a better understanding of foetal and childhood exposure to ELF fields, especially from residential exposure to underfloor electrical heating and from transformers in apartment buildings.

It is suspected that in some cases of occupational exposure the present ELF guideline limits are exceeded. More information is needed on exposure (including to non-power frequencies) related to work on, for example, live-line maintenance, work within or near the bore of MRI magnets (and hence to gradient-switching ELF fields) and work on transportation systems. Similarly, additional knowledge is needed about general public exposure which could come close to guideline limits, including sources such as security systems, library degaussing systems, induction cooking and water heating appliances.

Exposure to contact currents has been proposed as a possible explanation for the association of ELF magnetic fields with childhood leukaemia. Research is needed in countries other than the USA to assess the capability of residential electrical grounding and plumbing practices to give rise to contact currents in the home. Such studies would have priority in countries with important epidemiological results with respect to ELF and childhood leukaemia.

2.2 DOSIMETRY

In the past, most laboratory research was based on induced electric currents in the body as a basic metric and thus dosimetry was focused on this quantity. Only recently has work begun on exploring the relationship between external exposure and induced electric fields. For a better understanding of biological effects, more data on internal electric fields for different exposure conditions are needed.

Computation should be carried out of internal electric fields due to the combined influence of external electric and magnetic fields in different configurations. The

vectorial addition of out-of-phase and spatially varying contributions of electric and magnetic fields is necessary to assess basic restriction compliance issues.

Very little computation has been carried out on advanced models of the pregnant woman and the foetus with appropriate anatomical modelling. It is important to assess possible enhanced induction of electric fields in the foetus in relation to the childhood leukaemia issue. Both maternal occupational and residential exposures are relevant here.

There is a need to further refine micro-dosimetric models in order to take into account the cellular architecture of neural networks and other complex suborgan systems identified as being more sensitive to induced electric field effects. This modelling process also needs to consider influences in cell membrane electrical potentials and on the release of neurotransmitters.

2.3 BIOPHYSICAL MECHANISMS

There are three main areas where there are obvious limits to the current understanding of mechanisms: the radical pair mechanism, magnetic particles in the body and signal-to-noise ratios in multicell systems, such as neuronal networks.

The radical pair mechanism is one of the more plausible low-level interaction mechanisms, but it has yet to be shown that it is able to mediate significant effects in cell metabolism and function. It is particularly important to understand the lower limit of exposure at which it acts, so as to judge whether this could or could not be a relevant mechanism for carcinogenesis. Given recent studies in which reactive oxygen species were increased in immune cells exposed to ELF fields, it is recommended that cells from the immune system that generate reactive oxygen species as part of their immune response be used as cellular models for investigating the potential of the radical pair mechanism.

Although the presence of magnetic particles (magnetite crystals) in the human brain does not, on present evidence, appear to confer a sensitivity to environmental ELF magnetic fields, further theoretical and experimental approaches should explore

whether such sensitivity could exist under certain conditions. Moreover, any modification that the presence of magnetite might have on the radical pair mechanism discussed above should be pursued.

The extent to which multicell mechanisms operate in the brain so as to improve signal-to-noise ratios should be further investigated in order to develop a theoretical framework for quantifying this or for determining any limits on it. Further investigation of the threshold and frequency response of the neuronal networks in the hippocampus and other parts of the brain should be carried out using in vitro approaches.

2.4 NEUROBEHAVIOUR

It is recommended that laboratory-based volunteer studies on the possible effects on sleep and on the performance of mentally demanding tasks be carried out using harmonized methodological procedures. There is a need to identify dose-response relationships at higher magnetic flux densities than used previously and a wide range of frequencies (i.e. in the kilohertz range).

Studies of adult volunteers and animals suggest that acute cognitive effects may occur with short-term exposures to intense electric or magnetic fields. The characterization of such effects is very important for the development of exposure guidance, but there is a lack of specific data concerning field-dependent effects in children. The implementation of laboratory-based studies of cognition and changes in electroencephalograms (EEGs) in people exposed to ELF fields is recommended, including adults regularly subjected to occupational exposure and children.

Behavioural studies on immature animals provide a useful indicator of the possible cognitive effects on children. The possible effects of pre- and postnatal exposure to ELF magnetic fields on the development of the nervous system and cognitive function should be studied. These studies could be usefully supplemented by investigations into the effects of exposure to ELF magnetic fields and induced electric fields on nerve cell growth using brain slices or cultured neurons.

There is a need to further investigate potential health consequences suggested by experimental data showing opioid and cholinergic responses in animals. Studies examining the modulation of opioid and cholinergic responses in animals should be extended and the exposure parameters and the biological basis for these behavioural responses should be defined.

2.5 NEUROENDOCRINE SYSTEM

The existing database of neuroendocrine response does not indicate that ELF exposure would have adverse impacts on human health. Therefore no recommendations for additional research are given.

2.6 NEURODEGENERATIVE DISORDERS

Several studies have observed an increased risk of amyotrophic lateral sclerosis in "electrical occupations". It is considered important to investigate this association further in order to discover whether ELF magnetic fields are involved in the causation of this rare neurodegenerative disease. This research requires large prospective cohort studies with information on ELF magnetic field exposure, electric shock exposure as well as exposure to other potential risk factors.

It remains questionable whether ELF magnetic fields constitute a risk factor for Alzheimer's disease. The data currently available are not sufficient and this association should be further investigated. Of particular importance is the use of morbidity rather than mortality data.

2.7 CARDIOVASCULAR DISORDERS

Further research into the association between ELF magnetic fields and the risk of cardiovascular disease is not considered a priority.

2.8 IMMUNOLOGY AND HAEMATOLOGY

Changes observed in immune and haematological parameters in adults exposed to ELF magnetic fields showed inconsistencies, and there are essentially no research data available for children. Therefore, the recommendation is to conduct studies on the effects of ELF exposure on the development of the immune and haematopoietic systems in juvenile animals.

2.9 REPRODUCTION AND DEVELOPMENT

There is some evidence of an increased risk of miscarriage associated with ELF magnetic field exposure. Taking into account the potentially high public health impact of such an association, further epidemiological research is recommended.

2.10 CANCER

Resolving the conflict between epidemiological data (which show an association between ELF magnetic field exposure and an increased risk of childhood leukaemia) and experimental and mechanistic data (which do not support this association) is the highest research priority in this field. It is recommended that epidemiologists and experimental scientists collaborate on this. For new epidemiological studies to be informative they must focus on new aspects of exposure, potential interaction with other factors or on high exposure groups, or otherwise be innovative in this area of research. In addition, it is also recommended that the existing pooled analyses be updated, by adding data from recent studies and by applying new insights into the analysis.

Childhood brain cancer studies have shown inconsistent results. As with childhood leukaemia, a pooled analysis of childhood brain cancer studies should be very informative and is therefore recommended. A pooled analysis of this kind can inexpensively provide a greater and improved insight into the existing data, including

the possibility of selection bias and, if the studies are sufficiently homogeneous, can offer the best estimate of risk.

For adult breast cancer more recent studies have convincingly shown no association with exposure to ELF magnetic fields. Therefore further research into this association should be given very low priority.

For adult leukaemia and brain cancer the recommendation is to update the existing large cohorts of occupationally exposed individuals. Occupational studies, pooled analyses and meta-analyses for leukaemia and brain cancer have been inconsistent and inconclusive. However, new data have subsequently been published and should be used to update these analyses.

The priority is to address the epidemiological evidence by establishing appropriate in vitro and animal models for responses to low-level ELF magnetic fields that are widely transferable between laboratories.

Transgenic rodent models for childhood leukaemia should be developed in order to provide appropriate experimental animal models to study the effect of ELF magnetic field exposure. Otherwise, for existing animal studies, the weight of evidence is that there are no carcinogenic effects of ELF magnetic fields alone. Therefore high priority should be given to in vitro and animal studies in which ELF magnetic fields are rigorously evaluated as a co-carcinogen.

With regard to other in vitro studies, experiments reporting the genotoxic effects of intermittent ELF magnetic field exposure should be replicated.

2.11 PROTECTIVE MEASURES

Research on the development of health protection policies and policy implementation in areas of scientific uncertainty is recommended, specifically on the use of precaution, the interpretation of precaution and the evaluation of the impact of precautionary measures for ELF magnetic fields and other agents classified as "possible human carcinogens". Where there are uncertainties about the potential health risk an agent poses for society, precautionary measures may be warranted in

order to ensure the appropriate protection of the public and workers. Only limited research has been performed on this issue for ELF magnetic fields and because of its importance, more research is needed. This may help countries to integrate precaution into their health protection policies.

Further research on risk perception and communication which is specifically focused on electromagnetic fields is advised. Psychological and sociological factors that influence risk perception in general have been widely investigated. However, limited research has been carried out to analyse the relative importance of these factors in the case of electromagnetic fields or to identify other factors that are specific to electromagnetic fields. Recent studies have suggested that precautionary measures which convey implicit risk messages can modify risk perception by either increasing or reducing concerns. Deeper investigation in this area is therefore warranted.

Research on the development of a cost – benefit/cost-effectiveness analysis for the mitigation of ELF magnetic fields should be carried out. The use of cost – benefit and cost-effectiveness analyses for evaluating whether a policy option is beneficial to society has been researched in many areas of public policy. The development of a framework that will identify which parameters are necessary in order to perform this analysis for ELF magnetic fields is needed. Due to uncertainties in the evaluation, quantifiable and unquantifiable parameters will need to be incorporated.

Table 1 Recommendations for further research

Topic	Priority
Sources, measurements and exposures	
Further characterization of homes with high ELF magnetic field exposure in different countries	Medium
Identify gaps in knowledge about occupational LF exposure, such as in MRI	High
Assess the ability of residential wiring outside the USA to induce contact currents in children	Medium
Dosimetry	
Further computational dosimetry relating external electric and magnetic fields to internal electric fields, particularly concerning exposure to combined electric and magnetic fields in different orientations	Medium

continued

Topic	Priority
Calculation of induced electric fields and currents in pregnant women and in the foetus	Medium
Further refinement of microdosimetric models taking into account the cellular architecture of neural networks and other complex suborgan systems	Medium
Biophysical mechanisms	
Further study of radical pair mechanisms in immune cells that generate reactive oxygen species as part of their phenotypic function	Medium
Further theoretical and experimental study of the possible role of magnetite in ELF magnetic field sensitivity	Low
Determination of threshold responses to internal electric fields induced by ELFs on multicell systems, such as neural networks, using theoretical and in vitro approaches	High
Neurobehaviour	
Cognitive, sleep and EEG studies in volunteers, including children and occupationally exposed subjects, using a wide range of ELF frequencies at high flux densities	Medium
Studies of pre- and post-natal exposure on subsequent cognitive function in animals	Medium
Further study of opioid and cholinergic responses in animals	Low
Neurodegenerative disorders	
Further studies of the risk of amyotrophic lateral sclerosis in "electric" occupations and in relation to ELF magnetic field exposure and of Alzheimer's disease in relation to ELF magnetic field exposure	High
Immunology and haematology	
Studies of the consequences of ELF magnetic field exposure on immune and haematopoietic system development in juvenile animals	Low
Reproduction and development	
Further study of the possible link between miscarriage and ELF magnetic field exposure	Low
Cancer	
Update existing pooled analyses of childhood leukaemia with new information	High
Pooled analyses of existing studies of childhood brain tumour studies High Update existing pooled and meta-analyses of adult leukaemia and brain tumour studies and of cohorts of occupationally exposed individuals	Medium
Development of transgenic rodent models of childhood leukaemia for use in ELF studies	High
Evaluation of co-carcinogenic effects using in vitro and animal studies	High

continued

Topic	Priority
Attempted replication of in vitro genotoxicity studies	Medium
Protective measures	
Research on the development of health protection policies and policy implementation in areas of scientific uncertainty	Medium
Further research on risk perception and communication focused on electromagnetic fields	Medium
Development of a cost – benefit/cost-effectiveness analysis for the mitigation of ELF fields	Medium