Polonium-210 poisoning: a first-hand account

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Summary

Background **Polonium-210 (^{210}Po) gained widespread notoriety after the poisoning and subsequent death of Mr Alexander Litvinenko in London, UK, in 2006. Exposure to ^{210}Po resulted initially in a clinical course that was indistinguishable from infection or exposure to chemical toxins, such as thallium.**

Methods **A 43-year-old man presented to his local hospital with acute abdominal pain, diarrhoea, and vomiting, and was admitted to the hospital because of dehydration and persistent gastrointestinal symptoms. He was initially diagnosed with gastroenteritis and treated with antibiotics. *Clostridium difficile* toxin was subsequently detected in his stools, which is when he first raised the possibility of being poisoned and revealed his background and former identity, having been admitted under a new identity with which he had been provided on being granted asylum in the UK. Within 6 days, the patient had developed thrombocytopenia and neutropenia, which was initially thought to be drug induced. By 2 weeks, in addition to bone marrow failure, he had evidence of alopecia and mucositis. Thallium poisoning was suspected and investigated but ultimately dismissed because blood levels of thallium, although raised, were lower than toxic concentrations. The patient continued to deteriorate and within 3 weeks had developed multiple organ failure requiring ventilation, haemofiltration, and cardiac support, associated with a drop in consciousness. On the 23rd day after he first became ill, he suffered a pulseless electrical activity cardiorespiratory arrest from which he could not be resuscitated and was pronounced dead.**

Findings **Urine analysis using gamma-ray spectroscopy on day 22 showed a characteristic 803 keV photon emission, raising the possibility of ^{210}Po poisoning. Results of confirmatory analysis that became available after the patient's death established the presence of ^{210}Po at concentrations about 10^9-times higher than normal background levels. Post-mortem tissue analyses showed autolysis and retention of ^{210}Po at lethal doses in several organs. On the basis of the measured amounts and tissue distribution of ^{210}Po, it was estimated that the patient had ingested several 1000 million becquerels (a few GBq), probably as a soluble salt (eg, chloride), which delivered very high and fatal radiation doses over a period of a few days.**

Interpretation **Early symptoms of ^{210}Po poisoning are indistinguishable from those of a wide range of chemical toxins. Hence, the diagnosis can be delayed and even missed without a high degree of suspicion. Although body surface scanning with a standard Geiger counter was unable to detect the radiation emitted by ^{210}Po, an atypical clinical course prompted active consideration of poisoning with radioactive material, with the diagnosis ultimately being made with gamma-ray spectroscopy of a urine sample.**

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Introduction

Alexander Litvinenko (born Dec 4, 1962) was an officer of the Russian secret service who, in 2000, was granted asylum in the UK and is said by his widow to have begun working as a consultant for the British intelligence services. On Nov 1, 2006, Mr Litvinenko fell ill and was admitted to hospital. His illness was later attributed to poisoning with polonium-210 (^{210}Po), since substantial amounts of this highly toxic radionuclide were found in his body by the Health Protection Agency (now Public Health England). An inquest into Mr Litvinenko's death was opened and adjourned in November, 2006, due to outstanding criminal proceedings. The inquest was subsequently resumed when it became clear that the two men suspected of his murder could not be extradited from Russia. The inquest was suspended in July, 2014, to allow a public inquiry under the Inquiries Act 2005 to take place. The inquiry's public hearing commenced at the Royal Courts of Justice in London in January, 2015, and included review of the patient's medical records, clinical course, spectroscopy results, and statements from experts. The hearing concluded on July 31, 2015, and the final report into the death of Mr Litvinenko was published on Jan 21, 2016.

Following the public hearing, the primary clinicians and toxicology experts involved in the care of Mr Litvinenko in 2006 are now free of any restrictions to describe the clinical aspects of this highly unusual case. In this report, we provide a first-hand account of the events leading to the diagnosis of ^{210}Po poisoning, as well as the detailed toxico-kinetics of the first documented case of lethal poisoning with polonium.

Presentation

On Nov 3, 2006, a 43-year-old man named Edwin Carter presented to the Accident and Emergency department of Barnet General Hospital (now part of Royal Free Hospital, London) complaining of abdominal pain, vomiting, and

	Haematological parameters					Liver and renal biochemistry			
	Haemoglobin concentration (g/L)	White blood cells (×10⁹/L)	Neutrophils (×10⁹/L)	Lymphocytes (×10⁹/L)	Platelets (×10⁹/L)	Bilirubin (μmol/L)	Alanine transaminase level (IU/L)	Urea (mmol/L)	Creatinine (μmol/L)
Day 3	201	21·7	19·8	1·0	178	49	16	12·1	101
Day 4	..	..	..	..	..	..	..	..	..
Day 5	149	17·2	16·1	0·6	105	..	..	7·9	76
Day 6	..	..	..	..	..	..	..	..	..
Day 7	130	7·1	6·8	0·1	92	..	..	4·4	79
Day 8	..	..	..	..	..	..	..	..	..
Day 9	129	1·3	1·1	0·0	63	66	50	4·6	76
Day 10	..	..	..	..	..	..	..	..	..
Day 11	136	0·3	0·3	0·0	35	60	92	4·4	90
Day 12	147	0·2	0·1	0·0	21	69	107	..	..
Day 13	145	0·1	0·0	0·0	9	76	102	..	..
Day 14	113	0·0	0·0	0·0	2*	..	..	10	102
Day 15	..	0·0	0·0	0·0	17	..	..	..	..
Day 16	..	0·0	0·0	0·0	21	..	..	..	..
Day 17	..	0·0	0·0	0·0	13	..	..	..	..
Day 18	91	0·1	0·0	0·0	10	153	40	9·2	132
Day 19	84	0·01	0·0	0·0	7	181	34	9·8	133
Day 20	91	0·01	0·0	0·0	15	228	39	11·8	190
Day 21	82	0·05	0·0	0·0	18	242	48	16·6	218
Day 22	90	0·01	0·0	0·0	8	254	54	23·9	286†
Day 23	108	0·02	0·0	0·0	15	158	112	24	353†
Normal levels (reference range)	120–180	4–11	2·0–7·5	1·0–4·0	150–400	3–20	5–50	3·5–6·5	60–120

*Platelet and plasma transfusions started. †Enzymatic creatinine.

Table 1: **Progression of the patient's haematological parameters and hepatic and renal biochemistry after suspected poisoning on day 1**

diarrhoea, which had started on Nov 1, 2006 (designated as day 1 in the following chronology). On examination, he appeared dehydrated. He was afebrile and had a normal pulse and blood pressure. Abdominal examination revealed epigastric tenderness. In view of the profuse nature of his diarrhoea, a provisional diagnosis of gastroenteritis, possibly of infective origin, was made. He was admitted for further investigation and started on intravenous fluids and oral ciprofloxacin 500 mg every 12 h. Investigations showed that serum urea and conjugated bilirubin concentrations were mildly raised at 12·1 mmol per L and 49 μmol per L, respectively, and creatinine was high at 101 μmol per L, suggesting dehydration. Haemoglobin concentration was 201 g per L (reference range 120–180 g/L) associated with a leucocytosis (white blood cell count 22×10^9 cells/L; reference range $4\cdot0–11\cdot0\times10^9$ cells/L) and neutrophilia ($19\cdot8\times10^9$ cells/L; reference range $2\cdot0–7\cdot5\times10^9$/L; table 1).

Clinical course

On day 7, *Clostridium difficile* toxin was identified in the patient's stools by the microbiology department at Barnet General Hospital. The possibility was raised that this finding might have been secondary to ciprofloxacin. When the diagnosis was discussed with the patient, he revealed his previous identity and suggested the possibility of being poisoned. He disclosed that before coming to the UK he had been known as Alexander Litvinenko and that he had defected from the Russian Security Service. Mr Litvinenko explained that on the day he became ill, he had met with former Komitet gosudarstvennoy bezopasnosti (KGB) agents and feared that he had been poisoned (figure 1, table 1). The patient and his wife asked medical staff whether poisoning by infection with *C difficile* might have occurred since they had a friend who had been killed in this way. Mr Litvinenko was commenced on oral metronidazole (400 mg three times daily) but his gastrointestinal symptoms persisted. The working diagnosis was of *C difficile* diarrhoea associated with a possible underlying viral gastroenteritis. By day 9, Mr Litvinenko had become neutropenic with a neutrophil count $1\cdot1\times10^9$ per L (table 1). His platelet count had also fallen from normal levels to 63×10^9 per L. The cause of the cytopenia was unknown but thought to be due to a viral gastroenteritis or a consequence of ciprofloxacin toxicity.

On day 11, his neutrophil count was lower than $0\cdot5\times10^9$ per L and he had spiked a fever. He was started empirically on intravenous piperacillin–tazobactam (4·5 g every 6 h) to avoid progression to a sepsis syndrome. He was also given one dose of pegylated G-CSF (Neulasta,

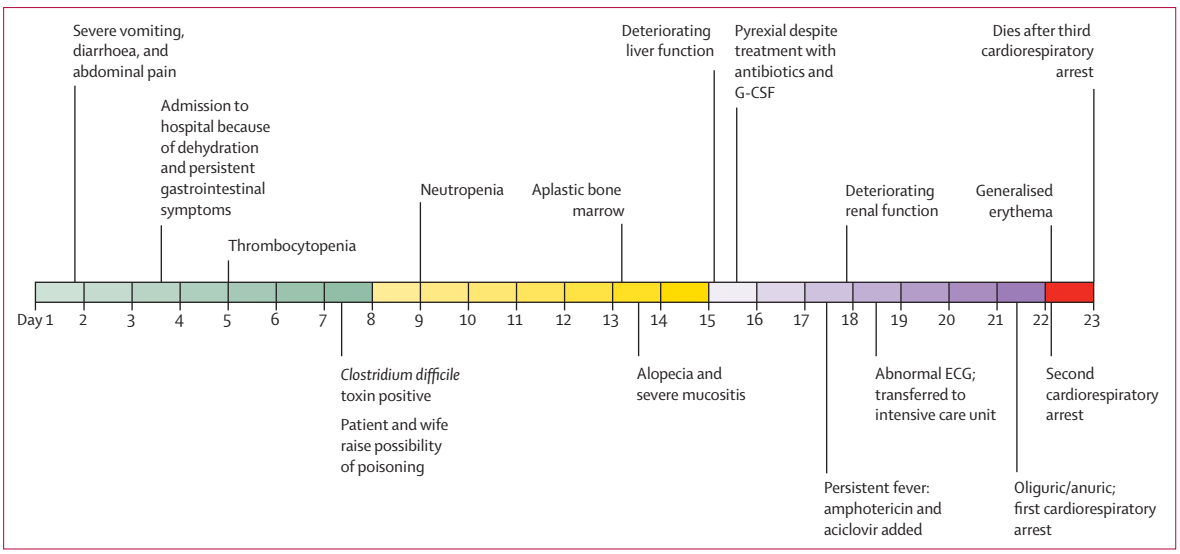

Figure 1: **Schematic of clinical milestones following exposure to polonium-210 on day 1**

6 mg [Amgen, CA, USA]) to stimulate recovery of the neutrophil count. By day 13, he had developed alopecia and mucositis; together with progressive cytopenia, these signs gave him the appearance of someone who had been exposed to toxin, chemotherapy, or radiation. Once again the patient and his wife raised the concern that he might have been poisoned, stating that many of his symptoms were similar to those he had learned about during his training as an agent in the Federal Security Service of Russia (FSB). Reverse barrier nursing was started and on toxicological advice from the clinical toxicology unit at Guy's & St Thomas' NHS Foundation Trust, London, UK, samples were sent to this clinical toxicology unit for a heavy metal screen. A screen of the patient with a standard Geiger counter revealed only background values. On the evening of day 16, the results of the heavy metal screen showed a slightly increased urine thallium concentration (30 nmol/L; normal <10 nmol/L) but this level was below the toxic concentration (800–1000 nmol/L). A bone marrow trephine sample taken on day 15 was acellular (figure 2). He was therefore transferred on day 17 to the haematology unit at University College London for specialist support and treatment of bone marrow failure. Samples were sent for human leucocyte antigen typing in case a bone marrow transplant was needed. The patient had told staff that the Russians used radioactive thallium as a poison. However, it was not thought likely that thallium poisoning was the cause of the patient's deterioration, especially since he had no evidence of peripheral neuropathy, which is a key feature of thallium poisoning. However, in the absence of any other clear cause, we started treatment with oral Prussian blue (ferric ferrocyanide; 4 g, every 8 h) because of the mildly raised urine thallium concentration together with gastrointestinal symptoms and alopecia—two clinical features that are typically associated with thallium poisoning.

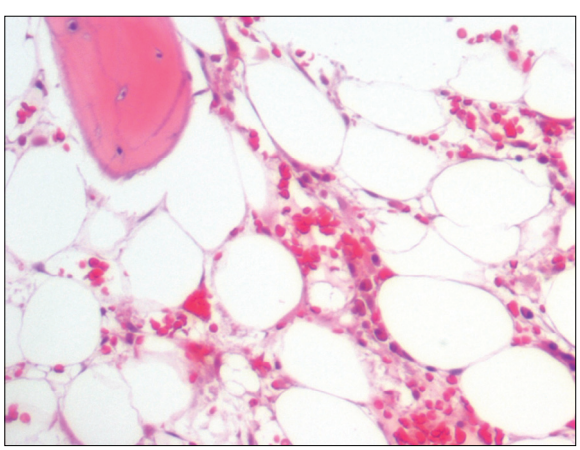

Figure 2: **Haematoxylin and eosin-stained bone marrow trephine showing cartilage and adipocytes with very few haemopoietic precursors**

On day 18, he was jaundiced with normal alanine transaminase levels. Diarrhoea and abdominal pain were settling and his oral intake was improving, although he had haematemesis that evening. On day 19, the rapid assessment team was called because of concerns about heart rate irregularity: inverted T-waves were noted on the lateral leads of an electrocardiogram. Troponin T levels were normal. Nevertheless, he was transferred to the intensive care unit for further monitoring. To mitigate against further heart rhythm abnormalities, serum potassium was maintained at about 5·5 mmol per L. He remained pyrexial, despite antibiotics. Because of raised inflammatory markers (C-reactive protein 100 mg/mL, erythrocyte sedimentation rate 130 mm/h) but no evidence of disseminated intravascular coagulation, he was started on systemic antifungal therapy with Ambisone (Gilead, CA, USA). Repeat analyses of plasma and urine showed a normal thallium concentration

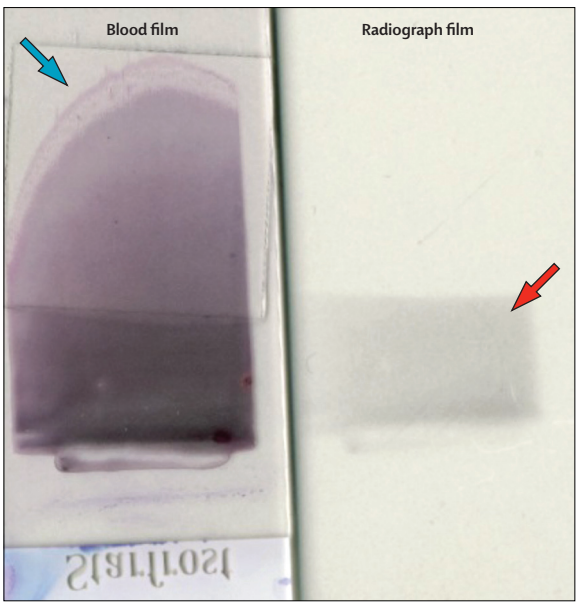

Figure 3: **Radiograph film (right image) exposed to the patient's blood smear (left image) showing opacification (red arrow) in the exposed area of the smear but not in the adjacent area that was covered by a glass coverslip (blue arrow)**

	Activity, Bq per g of tissue	Total estimated activity in organ or tissue, MBq*	Model prediction of total activity in organ or tissue, MBq†
Muscle (psoas)	1100	72	71‡
Brain	5500	8	..
Lung	3500	1·8	..
Spleen	9900	1·5	4·5
Kidney	49 000	15	17
Bile	13 000	3–14 per day	4§
Liver	30 000	54	66
Heart	2500	2¶	..
Skin	1800	6	35
Blood: day 20	3300	19	25
Blood: day 23	1500	8	23
Urine: day 22	825 per mL	1·3	1·0

Bq=becquerel. MBq=megabecquerel. *Scaled from measurements using data for organ masses, and blood, urine, and bile volumes.[1] †An estimate of intake by ingestion of 4·4 GBq polonium-210 on day 1, assuming 10% absorption to blood, was made based on the most reliable measurements (urine, liver, and kidneys) using a model for the behaviour of polonium-210 in the body[2] and the model was then used to calculate the tabulated values. ‡Assuming that the concentration of polonium-210 in muscle is representative of "other" tissues in the model.[2] §Based on the assumption that biliary excretion accounts for all faecal excretion. ¶Including blood content.

Table 2: **Measurements of polonium-210 in post-mortem samples and model predictions of organ content and excretion**

(<10 nmol/L). By this stage, his conjugated bilirubin level was high (230 µmol/L). During the following 2 days (days 20–22) his renal function deteriorated rapidly (table 1). An abdominal ultrasound scan showed that the liver, spleen, and kidneys were of normal size and appearance, with no evidence of obstruction.

The possibility of chemotherapeutic agents causing mucositis and bone marrow failure was considered but dismissed because covert administration at the doses necessary to cause rapid multi-organ failure would have been difficult. A search for a radiotoxin was pursued along several lines. Exposure of the patient's blood smear on a glass slide to a radiograph film on day 22 showed that the radiograph film exposed to parts of the blood smear not covered by a glass coverslip developed opacity (figure 3), which is consistent with the presence of a radioactive substance in the blood. Later that day, gamma-ray spectrometry measurements on a urine sample from the patient showed a characteristic 803 keV photon emission, raising the possibility of polonium-210 (^{210}Po) poisoning. Further urine and blood samples were sent for confirmatory spectrometric analysis. However, the patient's condition deteriorated rapidly that day with the onset of a florid macular skin rash, abdominal distension, progressive metabolic acidosis, and oliguria. He became hypothermic (35·5°C) and progressed to cardiogenic shock with an associated acute drop in consciousness. This was followed rapidly by a pulseless electrical activity cardiorespiratory arrest. He was resuscitated successfully but was dependent on escalating doses of epinephrine, and had a further pulseless electrical activity cardiac arrest 2 h later. Echocardiography showed poorly contracting ventricles with no evidence of tamponade or valvular pathology. Oesophageal Doppler showed a stroke volume of 40 mL (normal stroke volume is 70 mL) despite high doses of epinephrine (2·0 µg/kg per min). For the next 16 h the patient remained unstable and required inotropes, continuous veno-venous haemofiltration, and full mechanical ventilation. On day 23, Mr Litvinenko suffered a third pulseless electrical activity cardiac arrest and was pronounced dead. Results of the day 22 urine sample became available shortly after the patient's death and showed the presence of 825 becquerel (Bq) per mL of ^{210}Po, consistent with polonium poisoning.

Post-mortem results

A post-mortem examination was done by a consultant forensic pathologist on day 31 in the presence of a radiation protection officer. Precautions to avoid radiation exposure included the wearing of protective suits, gloves taped at the wrists, and large battery-operated plastic hoods into which filtered air was piped. Key gross macroscopic findings were the presence of blood-tinged fibrinous pericarditis, a pleural effusion associated with bilateral congestion of the lungs, gross ascites, and generalised tissue autolysis of most organs, although the brain looked normal. Because of continuing autolysis of tissues resulting from their ^{210}Po content, and the hazardous nature of the tissue samples, microscopy of the internal organs was not done and further analyses were limited to studies of the biodistribution of ^{210}Po

using gamma-ray spectrometry. The results were used to estimate total organ concentrations of ^{210}Po at the time of death. As table 2 shows, ^{210}Po was retained in all organs and tissues, with the highest activity in the liver (30 MBq/g) and kidney (49 MBq/g), consistent with published data on the biodistribution of ^{210}Po.[2–4] The lower concentration of ^{210}Po in lung tissue (3·5 MBq/g) was consistent with intake by ingestion. On the assumption of ^{210}Po ingestion on day 1 with 10% being absorbed into the systemic circulation, the concentrations of ^{210}Po measured in the liver, kidneys, and urine were used to estimate intake as 4400 MBq (4·4 GBq)[2,4]

We estimated the cumulative radiation doses to the organs of a reference 70 kg adult man over 22 days following the ingestion of 4·4 GBq of ^{210}Po (table 3). Radiation doses causing lethal damage to body organs are generally quantified in terms of the lethal dose of acute gamma radiation estimated to kill 50% of people exposed in this way (lethal dose 50 [LD_{50}] values), with corresponding LD_0–LD_{100} ranges. Doses necessary to cause prodromal symptoms of vomiting and diarrhoea are expressed as effective doses (however, it should be noted that LD and effective dose [ED] are toxicological terms and ED should not to be confused with the radiation protection quantity of effective dose). When estimating values for ^{210}Po, it was necessary to take account of the reduced effectiveness of protracted irradiation and the greater damage caused per Gy by alpha particles compared with gamma rays (ie, the relative biological effectiveness for alpha particles is >1). Taking account of dose protraction and assuming a relative biological effectiveness of 2, the ED_0 and ED_{50} values for vomiting and diarrhoea were estimated to be about 0·6–0·8 Gy and 7 Gy, respectively.[4] Therefore, our estimated dose rate to all regions of the gut of about 0·2 Gy per day for the first few days after intake (table 3) does not seem to be sufficient to cause the prodromal symptoms the patient experienced. However, the model might have underestimated gut doses, especially since data from animals suggest that a proportion of ingested ^{210}Po is retained in the gastric and intestinal mucosa.[4] Alternatively, these symptoms might have been caused by or compounded by infection with *C difficile* or a cumulative radiation dose delivered by the radiotoxin in the gut lumen as well as that absorbed into the bloodstream. By contrast, the estimated dose to the red bone marrow was about 6 Gy after 1 week, rising to 17 Gy after 22 days. The estimated radiation doses to the liver and kidneys were also very high—about 5 Gy to the liver and 9 Gy to the kidneys per day over the first few days and reaching 92 Gy and 140 Gy, respectively, after 22 days.

	Cumulative dose (Gy)						
	Red bone marrow	Gut	Liver	Kidneys	Spleen	Skin	Testes
1 day after intake	0·8	0·2	5·0	8·1	2·9	0·6	0·8
2 days after intake	1·8	0·4	11	18	6·4	1·3	1·9
3 days after intake	2·7	0·6	17	27	9·9	2·0	2·9
4 days after intake	3·6	0·8	22	36	13	2·8	4·1
5 days after intake	4·5	1·1	28	44	16	3·6	5·2
10 days after intake	8·7	2·0	51	80	31	7·9	12
15 days after intake	12	2·8	70	110	44	13	19
20 days after intake	16	3·5	86	130	55	18	26
22 days after intake	17	3·7	92	140	59	20	29

GBq=gigabecquerels. 1 Bq=1 dissociation per second (releasing one alpha particle per second, with associated low-yield [10^{-5}] gamma rays). 1 Gy=1 joule per kg.

Table 3: **Cumulative doses to organs or tissues of a reference adult man after ingestion of 4·4 GBq of polonium-210, assuming 10% absorption to blood**

Discussion

Polonium-210 is a naturally occurring radioactive element that was discovered in 1898 by Marie Curie. It decays to stable lead-206 by emitting one alpha particle, with occasional excitation in the nucleus and emission of 803 keV gamma rays. It has a half-life of 138 days and high specific activity, so that a very small mass corresponds to a high amount of radioactivity. Human beings are constantly exposed to ^{210}Po, which occurs at low concentrations in the environment as part of the uranium decay chain. However, annual intake from natural sources is about 10^8 times less than the intake estimated in our patient at around 4 GBq.

Polonium is used in various industrial processes and as a power supply in small satellites, but its manufacture requires sophisticated equipment. It is, therefore, not widely available, but it is an effective poison. It forms water-soluble, colourless salts that are readily absorbed across biological membranes, becoming widely distributed in body organs and tissues where the alpha particles deliver a large amount of energy to surrounding cells, causing cell death and organ damage. Early symptoms of ^{210}Po poisoning are indistinguishable from those of a wide range of chemical toxins. Therefore, the diagnosis can be delayed and even missed without a high degree of suspicion. Furthermore, ^{210}Po can be transported easily and safely without detection because its high-energy alpha particles have a short range and can be blocked by quite a thin barrier, such as the skin, and the associated gamma-ray emissions are very low yield. Hence, the Geiger counter used in this case was unable to detect the radiation emitted by ^{210}Po. Alpha-particle spectroscopy is the best way to test for radiotoxins such as ^{210}Po that emit alpha particles. However, these devices are not readily available in most hospitals.

Reports of ^{210}Po poisoning in human beings are scarce; a Russian accident case involving inhalation of an aerosol of ^{210}Po at a dose of about 530 MBq ^{210}Po resulted in death in 13 days.[4,5] However, the timecourse of rapid clinical deterioration observed in our patient, resulting in death within 23 days, is consistent with animal data for several mammalian species.[4] Aside from the gastrointestinal tract, the bone marrow was one of the first organ systems to be damaged. From an initial neutrophilia, a feature of acute

radiation injury,[6] the neutrophil count fell rapidly over a 2-week period. The LD_{50} for the bone marrow was estimated to be about 3 Gy, with an LD_0–LD_{100} range of 1–4 Gy. Our calculations indicate that the LD_{100} value for the red bone marrow was exceeded after 5 days (table 3), causing irreversible damage to the haemopoietic stem cell and stromal compartments.[4] At substantially lower doses of ^{210}Po, transplanted progenitor cells might provide transient support but animal data suggest that death in such a setting can occur later, mainly as a consequence of radiation damage to the kidneys.[7] Similarly, the estimated LD_{50} value for acute kidney damage was 6 Gy, with a corresponding value for liver failure of 8 Gy. Our estimates of the cumulative dose delivered to the kidney and liver were 44 and 28 Gy, respectively, at day 5. Hence, the wide distribution of ^{210}Po probably resulted in the delivery of lethal radiation doses to several organs early after intake.

Several chelating agents have been assessed in animal models of ^{210}Po poisoning to reduce organ retention and enhance excretion.[8,9] Unithiol (sodium 2,3-dimercaptopropane-1-sulphonate) has been used in children accidentally exposed to ^{210}Po in the former Soviet Union[10] and has recently been given to two individuals thought to have been exposed at around the same time as Mr Litvinenko: both survived, but both had received much lower doses of ^{210}Po than our patient. Animal data suggest that chelation can reduce ^{210}Po retention in the blood, spleen, and bone, although this might be associated with increased retention in the kidneys and the brain. Typically, the amounts used in animal studies are higher than recommended for administration to human beings.

Conclusion

This case has raised our awareness of the possibility that radioactive materials can be used as poisons with catastrophic effect. Importantly, early symptoms of ^{210}Po poisoning were indistinguishable from those of a wide range of chemical toxins, including thallium, thus causing a delay in diagnosis. Additionally, body surface scanning with a standard Geiger counter was unable to detect the alpha radiation emitted by ^{210}Po. Nevertheless, an atypical clinical course, including mucositis, alopecia, and bone marrow failure, prompted active consideration of poisoning with radioactive material, with the diagnosis ultimately being made with gamma-ray spectroscopy of a urine sample. An earlier diagnosis in our patient would not have enabled him to survive because the high amount of ^{210}Po absorbed and distributed to body organs within hours of intake would have resulted in rapid cell death and multiple organ failure. Preparedness for such cases in the future would need a high degree of clinical suspicion and investment in sensitive detection instrumentation by hospitals. However, such cases would remain untreatable without research into effective antidotes that reduce levels and biodistribution of ^{210}Po, and limit the extent of organ damage. Nevertheless, early diagnosis of poisoning with radiotoxin is important to maximise the potential for effective treatment and enable appropriate precautions to be taken to protect hospital staff.

Contributors

ACN, NG, DL, and JDH collated all the data and prepared the first draft of the report. ACN provided the University College London Hospital clinical data for the patient. JFD, JG, JY, and ACN provided the data relating to the intensive treatment unit management of the patient. PID provided toxicology input. JDH provided the polonium-210 biodistribution and dosimetry data. AV provided data from the initial management of the patient in Barnet General Hospital.

Declaration of interests

We declare no competing interests.

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References

1 International Commission on Radiological Protection. Basic anatomical and physiological data for use in radiological protection: reference values. ICRP Publication 89, report no. 32 (3–4). Oxford: Elsevier Science Ltd, 2002.

2 Leggett RW, Eckerman KF. A systemic biokinetic model for polonium. *Sci Total Environ* 2001; **275:** 109–25.

3 Fellman A, Ralston L, Hickman D, Ayres L, Cohen N. Polonium metabolism in adult female baboons. *Radiat Res* 1994; **137:** 238–50.

4 Harrison J, Leggett R, Lloyd D, Phipps A, Scott B. Polonium-210 as a poison. *J Radiol Prot* 2007; **27:** 17–40.

5 Ilyin LA. Radiation medicine guidance for medical researchers and health management. Radiation damage of humans. Volume 2. Bushmanov AY, Grigoriev YG, Guskova AK, et al, eds. Moscow: AT, 2001.

6 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1988 Report to the General Assembly with Annexes. Annex G. Early effects in man of high doses of radiation. New York: United Nations, 1988.

7 Bruenger FW, Lloyd RD, Taylor GN, Miller SC, Mays CW. Kidney disease in beagles injected with polonium-210. *Radiat Res* 1990; **122:** 241–51.

8 Gerber GB, Thomas RG, eds. Guidebook for the treatment of accidental internal radionuclide contamination of workers. Report no. 41. Ashford, UK: Nuclear Technology Publishing, 1992.

9 Jefferson RD, Goans RE, Blain PG, Thomas SH. Diagnosis and treatment of polonium poisoning. *Clin Toxicol* 2009; **47:** 379–92.

10 Guskova AK, Drutman RD, Malysheva MS, Soldatova VA. Dose assessment and the possibility of clinical recognition of disease associated with the ingestion of ^{210}Po into the human body. *Med Radiol* 1964; **62:** 51–60.