Evaluation of Toxicological Hazards from Medical Radioiodine Administration

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Introduction

Iodine-131 is a radioactive isotope that is routinely administered as sodium iodide-131 (NaI-131) by health-care providers to both diagnose and treat thyroid disease. Patients may receive between 1 μ Ci and 10 mCi for diagnostic procedures. Therapeutically, patients may be administered 1 to 300 mCi depending on whether they are being treated for hyperthyroidism (1 to 29 mCi) or thyroid cancer (30 to 300 mCi) [1, 2]. The mechanism by which radioiodine (RI) is taken up into the thyroid depends on a number of factors, including the functional status of the gland, the level of thyroid-stimulating hormone (TSH) in the blood, and the consumption of certain foods and medications [2, 3].

As RI undergoes radioactive decay by releasing energy in the form of gamma and beta radiation, safety precautions should be followed by those receiving RI to keep potential secondary

exposures to the public well within regulatory limits [4]. Health-care professionals who assist in the administration of RI to a patient, such as the prescribing physician and nuclear medicine technologist, usually provide safety instructions to the patient prior to RI administration and again before discharge from the clinic or hospital. These instructions include the minimum distance at which the patient should stand from others, instructions on washing clothes, and instructions on toilet use [1].

Although instructions are usually given as a safety precaution to patients receiving RI therapy, hospitals are not legally required to provide instructions if the amount of radiologic activity administered (≤ 7 mCi), or the dose rate of a patient, falls below a certain threshold (e.g., ≤ 0.02 mSv/h at a distance of 1 m) [1]. In addition, many patients may find it difficult to recall the exact instructions provided to them following their RI administration. Finally, instructions given may not be as detailed as needed when it comes to handling of objects contaminated with the patient's bodily fluids. Therefore, when a contamination incident occurs, patients may become concerned and seek the help of a health-care professional. If unable to reach their prescribing physician, they may contact a state or regional poison center for advice.

Poison centers rely on health-care professionals with specialized expertise in clinical toxicology, such as medical toxicologists, to provide comprehensive advice in radiologic exposures. This necessitates medical toxicologists knowing what precautions to take when dealing with RI exposure and contamination issues. In addition, it may be advantageous for medical toxicologists to understand the inherent characteristics of the radiopharmaceutical so that they may provide the best guidance possible to the public on how to handle contamination scenarios or radiation exposure concerns. It is important to note that this paper pertains to that of NaI-131 and may not be suitable for application with other radiopharmaceuticals. In addition, although fundamental concepts are introduced, the expertise of subject-matter experts and outside

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resources may be necessary to call on in order to fully address certain situations.

Important Concepts for Medical Toxicologists

A model is proposed to help medical toxicologists address concerns about RI contamination and exposure. It is based on the following six factors: (1) the dose of RI administered, (2) the date and time of administration, (3) the date and time of patient release from the clinic/hospital, (4) the nature of the procedure (in- or outpatient), (5) the ages of others in the home and/or workplace, and (6) the properties of any contaminated surfaces (smooth surfaces, hard surfaces such as hardwood flooring and tile that are easier to clean than soft, absorbent surfaces such as carpet). These six fundamental concepts will be discussed throughout this article. Which method a medical toxicologist uses to address concerns about RI contamination and exposure will depend on what information from the six factors introduced can be obtained (see Fig. 1).

Calculating Dose

Knowing what activity or dose of RI a patient received can be used by the medical toxicologist to determine how long that person can spend in proximity to others and what precautions may be needed when handling objects contaminated with bodily fluids. Although precautionary measures should be taken following any administration of RI, doses can vary by orders of magnitude depending on the indication for RI use. For this reason, exposures to others and contamination of bodily fluids can also vary greatly (see Table 1). It is critical to know that the RI dose used to treat thyroid cancer can be (and often is) much larger than that given for a diagnostic thyroid uptake procedure.

In order to best use the information introduced in Table 1, an understanding of three main concepts is needed: (1) RI's gamma constant, (2) the dose limit for the public, and (3) the decay equation. The *gamma constant* (or gamma ray constant) is a measure of radiation exposure from a gamma-releasing source; the resulting value depends on the original radioactivity of the source, expressed in units of millicuries. The gamma

Fig. 1 A model for medical toxicologists to use to help address concerns regarding medical radioiodine (RI) contamination and exposure. *Note:* Both the physical and biological half-lives should be taken in consideration when calculating dose equivalence rate for a given radionuclide. However, Fig. 1 only uses the physical half-life of NaI-131 (about 8 days

[4]) to estimate dose equivalence rate since the physical half-life holds more weight than the biological half-life for NaI-131 and for ease of calculation. See explanation on the effective half-life under “Understanding Relative Radiation Exposure” for further explanation

Table 1 Dose equivalence rate before and after RI administration

Activity administered (I-131)	Approximate dose equivalence rate (mSv/h at 1 m at the time of administration) ^a	Approximate dose equivalence rate (mSv/h at 1 m after 7 days post administration) ^{a, b}
1 μ Ci (37 kBq)	2E-6	1.2E-6
10 mCi (370 MBq)	0.02	0.012
29 mCi (1.07 GBq)	0.06	0.034
300 mCi (11.1 GBq)	0.62	0.35

^a The acceptable dose limit to the public coming from an individual internally contaminated with a radioactive material is 5 mSv (500 mrem) total effective dose equivalent (TEDE) [7]

^b Both the physical and biological half-lives should be taken in consideration when calculating dose equivalence rate for a given radionuclide. However, Table 1 only uses the physical half-life of NaI-131 (about 8 days [4]) to estimate dose equivalence rate since the physical half-life holds more weight than the biological half-life for NaI-131 and for ease of calculation. See explanation on the effective half-life under “Understanding Relative Radiation Exposure” for further explanation

constant is used to calculate an estimate of radiation exposure coming from an individual [measured in milliroentgen (mR)] per unit time [measured in hours (h)] at a distance of 1 m.¹ The gamma constant for I-131 is 0.22 mR/h at 1 m per mCi. This is equal to a dose equivalence rate of approximately 0.002 mSv/h at 1 m per mCi [5].

Dose limits for the public have been set by federal and international radiation protection agencies to help safeguard the public against potential adverse health effects resulting from low-level exposures to ionizing radiation [6]. The acceptable dose limit to the public coming from an individual internally contaminated with a radioactive material is set to be 5 mSv (500 mrem) total effective dose equivalent (TEDE) by the US Nuclear Regulatory Commission for the USA [8]. In general, the radiation dose limit to the public is set at 1 mSv in a year, not including “exposure to individuals administered radioactive material and released” according to the NRC [8]. The *decay equation* [$A = A_0(0.5^{t/T_{1/2}})$] is generally used to calculate a dose rate or activity (A) coming from an individual with a known initial dose rate or that was administered a known activity (A_0) after a specific period of time (t) has elapsed. The equation implies knowing the physical half-life of the radioactive material ($T_{1/2}$).

To calculate an individual’s likelihood of exposing others to more than 5 mSv, factors such as the physical half-life of I-131 (about 8 days [4]) and an occupancy factor at 1 m of 0.25 must be taken into consideration.² Individuals receiving RI usually follow instructions to maintain a certain distance from others, even adopting alternative sleeping arrangements, if necessary [12]. For the purposes of this article, we will assume the worst case scenario as it pertains to potential

radiation exposure. This assumes a 100 % I-131 uptake into the thyroid gland and an occupancy factor of 1. Using the decay equation, the dose equivalence rate can be calculated for an individual administered RI 7 days prior, for example. The calculations introduced in this article are based on the physical half-life of the isotope and do not take into consideration the biological half-life which is patient-specific.³ For a detailed and in-depth explanation into the factors considered when calculating radiation exposure, please refer to NUREG-1556, volume 9, revision 2 [9].

If an individual does not know how much I-131 they were given, the medical toxicologist may approximate a dose on the basis of the procedure performed or its indication. As noted above, diagnostic procedures such as thyroid scans generally involve the administration of lower doses of RI than do therapeutic procedures like thyroid ablation for hyperthyroidism or cancer. Having this information will permit the medical toxicologist to make an educated guess about the estimated range of administered activity.

Understanding Relative Radiation Exposure

Effective half-life is defined as the combined effects of the physical half-life (the inherent radioactive decay of an isotope) and the biological half-life (the rate at which biological processes such as excretion rid the isotope from the body). Effective half-life is calculated as follows:

$$(1 \div \text{Effective half-life}) = (1 \div \text{Physical half-life}) + (1 \div \text{Biological half-life})$$

The physical half-life of RI (which is much shorter than the biological half-life) has much more of an influence on the value of the effective half-life. For this reason, then, in this

¹ See Example Scenario B for further explanation on the use of the gamma constant.

² The occupancy factor of 0.25 implies that a person is present 25 % of the time at a certain distance from a source of radiation. The 5 mSv standard is based on a number of factors such as the occupancy factor, inputted into specific equations. Please see NUREG-1556, volume 9, revision 2 [9], for further guidance on these.

³ See calculations under Example Scenario A for an in-depth explanation on the use of the decay equation.

article, we have intentionally used the physical half-life, rather than the effective half-life in the decay equation. Taking this approach simplifies the calculations (biological half-life is variable, patient-specific, and procedure-specific) and provides the medical toxicologist with a “worst case scenario” on which to base their guidance. The effective half-life, however, is commonly used when performing radiation dosimetry [10].

As those patients released after RI therapy are not likely to exceed the 5 mSv exposure limit to the public, patients’ exposures to others will be low and unlikely to be clinically significant. It is important to compare a patient’s potential exposure to the public to other possible sources of radiation, such as an abdominal CT (approximately 8 mSv) or the dose of natural background radiation in the USA per year (average dose of 3.1 mSv) [11, 12]. Therefore, any calculated potential radiation exposures may be looked at in context to these common comparisons.

There are many factors and methods that are important to consider when determining individual cases of potential radiation exposure to the public. The fundamental safety steps considered important to follow by the Health Physics Society (<http://www.hps.org/publicinformation/radterms/radfact1.html>) include minimizing the *time* spent near a radioactive source and maximizing the *distance* away and *shielding* between a person and a radioactive source. Taken together, these three safety steps help to reduce radiation exposure and form the underpinnings of the radiation protection concept known as ALARA or “as low as reasonably achievable.” ALARA was used as the basis for recommendations for RI safety precautions from the American Thyroid Association. Medical toxicologists are encouraged to adhere to these principles as closely as possible [13, 14].

The following two example scenarios illustrate how the six fundamental concepts introduced earlier in this article can be used to address concerns following medical radioiodine administration.

Example Scenario A A 27-year-old female patient who has received radioiodine therapy for treatment of thyroid disease calls the poison center to determine how long she is able to be within close proximity to her co-workers and family before they receive a significant amount of radiation. She does not recall the amount of radioiodine she received, and she is not able to get in contact with her prescribing physician. She received her therapy as an inpatient and was allowed to leave in accordance with standard release rates 1 day ago.

If a patient does not recall the amount of RI they received but knows that they were admitted to the hospital as an inpatient for the RI administration, the toxicologist can estimate their dose equivalence rate or the potential activity of the contamination in their body fluids by utilizing *standard release rules*. Although regulations may vary from state to state, federal regulations promulgated by the US Nuclear

Regulatory Commission (10 CFR 35.75) state that a patient can be released from the hospital if, by coming into contact with that individual, a maximally exposed member of the public is not likely to be exposed to more than 5 mSv (500 mrem) [7].

Assuming a patient was discharged on the basis of the 5 mSv standard,⁴ this is equivalent to an activity of ≤ 33 mCi in the patient’s body [1, 9]. Many hospitals use the dose rate from a patient at 1 m to determine if a patient may be released [must be ≤ 0.07 mSv/h (7 mrem/h) at 1 m] [1, 9]. Although the toxicologist in our example does not know when the RI was administered, he or she can utilize the standard release rate and the radiation decay equation, $A = A_0(0.5^{t/T_{1/2}})$, to estimate the current approximate dose equivalence rate at a 1-m distance from the patient.⁵

The patient can be reassured to not worry about the external dose to members of the public who are at a distance of 1 m. The 5 mSv limit is a level of radiation dose for which a risk of disease is low [15].

A_0 is equal to exposure rate, dose equivalence rate, or amount of activity in the individual upon release from the hospital (dose equivalence rate used = 0.07 mSv/h exposure rate at 1 m). Toxicologists can assume the worst case scenario of a 0.07 mSv/h dose equivalence rate at 1 m at release. t is equal to the amount of time in days since release of individual (1 day), and $T_{1/2}$ (physical half-life) is equal to 8 days for I-131.

$$A = 0.07 \text{ mSv/h} \left(0.5^{1/8} \right) \\ = 0.064 \text{ mSv/h (current dose equivalence rate)}$$

The toxicologist can then find the amount of time (X) it would take for another individual to receive 5 mSv.

$$X = \frac{5 \text{ mSv}}{0.064 \text{ mSv/h}} = 78.125 \text{ h}$$

A member of the public would have to be at 1 m from the patient for about 78 h to reach the suggested maximum exposure limit at her current rate. This calculation assumes a constant dose equivalence rate, but by this time, the rate at which she emits radiation will have decreased as a result of both radioactive decay and biological elimination. Since biological elimination is not accounted for in the above calculation, the estimate is extremely conservative. If there is a situation where a patient is concerned with exposure to a

⁴ The 5 mSv and 33 mCi standard are based on a number of factors inputted into specific equations. Please see NUREG-1556, volume 9, revision 2 [9], for further guidance on these factors and the potential variance of patient-specific release rates.

⁵ Dose equivalence rate is different from exposure rate in that it takes into account the biological effect of different types of radiation. Exposure rate can be directly measured or determined from the radionuclide of interest and its activity.

member of the public who is closer than 1 m, for example a baby who is carried closely by a patient for a period of time, it may be important to call on outside resources, including subject-matter experts.

Toxicologists may also choose to pay close attention to the age and condition of patient's family members as children, infants, and fetuses of pregnant women are more susceptible to the potentially damaging effects of radiation [16]. If there is concern of exposure to a fetus or a child, toxicologists may consider seeking the assistance of additional specialists. Additionally, in potential cases where radiation exposure through the internalization of radioactive breast milk is of concern, the American Thyroid Association has gone so far as to recommend that breastfeeding be completely ceased for those patients who have received RI for a period of time. Since I-131 exits the body through secretions and excretions, such as urine, sweat, vomit, stool, saliva, breast milk, mucus, and blood, safety precautions are usually taken following RI administration to avoid unnecessary exposure to or ingestion of radioactive material [13]. Further, patients may not be given detailed instructions on how to handle objects they contaminate with radioactive body fluids and therefore may call upon a medical toxicologist for advice.

Example Scenario B The poison center received a call from the mother of a 10-year-old hyperthyroid girl who received a 10 mCi oral radioiodine tablet for radioablation. The patient sleepwalked and urinated on the wood laminate floor and also on her mother's bed. The mother attempted to contact the prescribing physician without success. The poison center contacted the on-call medical toxicologist who discussed appropriate decontamination and protection measures with the state radiation control program (RCP) officer. They recommended that the mattress be isolated in a different room as far away as possible from family members for 30 days and the clothes and bedding be washed twice separately. Since the floor was nonabsorbent, only normal cleaning techniques needed to be used while taking precautions to dispose of or isolate the materials used to clean the floor for 30 days to allow for decay. The state radiation control program proposed to survey the mattress after 30 days.

Assessing the radiological hazard in this case involves estimating the activity of RI in the thyroid and urine and on the contaminated surfaces. This patient received 10 mCi. Although uptake of the RI depends on multiple different factors and can vary, 100 % uptake will be assumed and an occupancy factor of 1.0 will be used in this article for simplicity when calculating the potential radiation exposure to the public as it applies to the 5 mSv release standard. By assuming 100 % uptake and an occupancy factor of 1.0, the calculated exposure will be more conservative than usual, meaning it will err on the side of caution.

Assuming the thyroid is a point source, the gamma constant for I-131 (approximately 0.002 mSv/h at 1 m per mCi) [5] yields a dose equivalence rate of 0.02 mSv/h from this point source ($10 \text{ mCi} \times 0.002 \text{ mSv/h/mCi at } 1 \text{ m} = 0.02 \text{ mSv/h}$). The dose limit not to be exceeded to a member of the public from a patient released after therapy is 5 mSv [7]. Thus, without considering decay, it would take about 250 h ($5 / 0.02 \text{ mSv/h}$) of close contact at 1 m to reach this level. It is hard to determine the amount of RI in the soiled mattress considering it is a variable fraction of the amount excreted in an unknown volume of urine. Due to this uncertainty, the worst case assumption is to assume that the entire dose of RI was present in the spilled body fluid and it is prudent to isolate the contaminated objects while decay occurs. If the soiled mattress is treated as a point source, it is found that after the elapse of four half-lives (32 days), the activity would decrease to 0.6 mCi [decay equation: $A = 10 \text{ mCi}(0.5^4)$, where 4 = number of half-lives]. At this level of exposure, it would take approximately 158 days of exposure at 1 m to reach the 5-mSv limit.

Additionally, a reduction in exposure may likely come with increased public awareness of the concepts addressed by the inverse-square law. It demonstrates that the greater the distance between contaminated objects or persons who have had RI and other members of the public, the better. The inverse-square law demonstrates the concept that by doubling the distance, radiation dose equivalence rates are decreased to one fourth their original rate [17].

For example, the contaminated mattress introduced in the example scenario could potentially have a dose equivalence rate of 0.02 mSv/h at 1 m considering the worst case scenario. By increasing the distance of the object to 2 m, the rate is decreased to 0.005 mSv/h. See calculations below as demonstrated by the inverse-square law.

$$\begin{aligned} \text{Intensity}_1 (\text{Distance}_1^2) &= \text{Intensity}_2 (\text{Distance}_2^2) \\ 0.02 \text{ mSv/h } (1 \text{ m})^2 &= X \text{ mSv/h } (2 \text{ m})^2 \\ \frac{0.02 \text{ mSv/h/1 m}}{4 \text{ m}} &= 0.005 \text{ mSv/h at } 2 \text{ m} \end{aligned}$$

Additionally, it is important to note that if an object cannot be considered to be a point source (cases where contamination is not isolated to a particular region on a large object), the inverse-square law may not be appropriate to use. In these cases, it may be prudent to isolate the object until a subject-matter expert, such as the state radiation control program, can monitor the object and area in order to make appropriate decisions.

Conclusion

In addition to the basic concepts introduced in this article, there may be a need to call on the guidance of subject-matter

experts or more in-depth resources if a specific case requires. It is also important to note that whenever possible, medical toxicologists may want to consider trying to contact prescribing physicians or hospitals of concerned patients before attempting to evaluate situations and provide advice.

Additionally, medical toxicologists may find it useful to refer to lists of radiological experts provided at poison centers which may include resources, such as the Radiation Emergency Assistance Center/Training Site (REAC/TS), or to call upon supplemental resources, such as state radiation control program officials, the nuclear medicine department, or the hospital radiation safety officer. Additionally, online tools such as the dosimetry guide, Radiation Dose Assessment Resource (RADAR) (<http://www.doseinfo-radar.com/RADARDoseRiskCalc.html>) [18], guidelines provided by the US Nuclear Regulatory Commission [9], and the resource provided by The American Thyroid Association Taskforce on Radioiodine Safety [13] are available. The Medical Procedure Dose Calculator and Risk Language Generator on the RADAR website, in particular, may be of help when the RI dose and procedure are known. Additional studies and reference materials pertaining to the topics covered in this article should also be referenced for more detailed and accurate estimations and advice [19–24].

In conclusion, while RI therapy is unlikely to involve clinically significant radiation exposures to the public, precautions can be followed in order to minimize radiation exposure. Medical toxicologists can assist the public in addressing concerns of potential radiation exposure by using calculations based on basic assumptions that will likely demonstrate the low risk of exposure from a patient treated with RI.

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References

- Shackett P (2009) Nuclear medicine technology: procedures and quick reference, 2nd edn. Wolters Kluwer/Lippincott Williams & Wilkins, Philadelphia, pp 492–493
- Mayo Clinic (2011) Sodium iodide I 131 (oral route). <http://www.mayoclinic.com/health/drug-information/DR601253>. Accessed 20 Aug 2013
- Balon HR, Silberstein EB, Meier DA, et al. (2006) Society of Nuclear Medicine procedure guideline for thyroid uptake measurement. <http://www.interactive.snm.org/docs/Thyroid%20Uptake%20Measure%20v3%200.pdf>. Accessed 25 Aug 2013
- U.S. EPA (2012) Iodine. <http://www.epa.gov/radiation/radionuclides/iodine.html>. Accessed 20 Aug 2013
- Shleien B, Birky BK, Slaback LAJ, Birky B, Slaback LA (1998) Health physics & radiological health handbook, 3rd edn. Lippincott Williams & Wilkins, Baltimore
- Health Physics Society. (2013) Regulatory dose limits. <http://www.hps.org/publicinformation/ate/faqs/regdoselimits.html>. Accessed 4 May 2014
- US NRC (2013) § 35.75 Release of individuals containing unsealed byproduct material or implants containing byproduct material. <http://www.nrc.gov/reading-rm/doc-collections/cfr/part035/part035-0075.html>. Accessed 4 May 2014
- US NRC (2013) § 20.1301 Dose limits for individual members of the public. <http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1301.html>. Accessed 4 May 2014
- Howe DB, Beardsley M, Bakhsh SR (2008) Consolidated guidance about materials licenses. Program-specific guidance about medical uses licenses (NUREG-1556, volume 9, revision 2). <http://www.pbadupws.nrc.gov/docs/ML0734/ML073400289.pdf>. Accessed 4 May 4, 2014
- Karesh S, Lipps M (2012) Half lives: physical, biological and effective. <http://www.nucmedtutorials.com/dwhalf/effective.html>. Accessed 21 Sep 2013
- US FDA (2009) What are the radiation risks from CT? <http://www.fda.gov/radiation-emittingproducts/radiationemittingproductsandprocedures/medicalimaging/medicalx-rays/ucm115329.htm>. Accessed 21 Sep 2013
- National Council on Radiation Protection & Measurements (2009) NCRP report no. 160, ionizing radiation exposure of the population of the United States. http://www.ncrponline.org/Publications/Press_Releases/160press.html. Accessed 4 June 2014
- Sisson JC, Freitas J, McDougall IR et al (2011) Radiation safety in the treatment of patients with thyroid diseases by radioiodine 131I: practice recommendations of the American Thyroid Association. *Thyroid* 21(4):335–346
- US NRC (2009) 10 CFR 20.1003 definitions. <http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1003.html>. Accessed 28 Aug 2013
- UNSCEAR. UNSCEAR 2006 report vol. I: report to the general assembly, scientific annexes A and B. http://www.unscear.org/unscear/en/publications/2006_1.html. Accessed 11 Nov 2013
- US EPA Agency (2012) Radiation protection. <http://www.epa.gov/radiation/topics.html>. Accessed 25 Aug 2013
- NDT Education Resource Center (2012) Radiographic inspection—formula based on Newton's inverse square law. <http://www.ndt-ed.org/GeneralResources/Formula/RTFormula/InverseSquare/InverseSquareLaw.htm>. Accessed 25 Aug 2013
- Stanford Dosimetry. RADAR—the radiation dose assessment resource. <http://www.doseinfo-radar.com/RADARDoseRiskCalc.html>. Accessed 4 May 2014
- International Commission on Radiological Protection (2004) Release of patients after therapy with unsealed radionuclides. *Annals ICRP* 34(2):v–vi, 1–79
- Leslie WD, Havelock J, Palser R, Abrams DN (2002) Large-body radiation doses following radioiodine therapy. *Nucl Med Comm* 23(11):1091–7
- Mathieu I, Caussin J, Smeesters P, Wambersie A, Beckers C (1999) Recommended restrictions after 131I therapy: measured doses in family members. *Health Phys* 76(2):129–36
- Zanzonico PB (1997) Radiation dose to patients and relatives incident to 131I therapy. *Thyroid* 7(2):199–204
- Barrington SF, O'Doherty MJ, Kettle AG, Thomson WH, Mountford PJ, Burrell DN, Farrell RJ, Batchelor S, Seed P, Harding LK (1999) Radiation exposure of the families of outpatients treated with radioiodine (iodine-131) for hyperthyroidism. *Eur J Nucl Med* 26(7):686–92
- Oak Ridge Institute for Science and Education. Radiation dose estimates and other compendia. <http://www.orise.ora.gov/reacts/resources/dose-estimates.aspx>. Accessed 4 June 2014