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In Vivo Thyroid Monitoring for Iodine-131 in the Environment*

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Monitoring of air and milk samples is done routinely around nuclear facilities that release iodine-131 to the environment. Results from these measurements are used to calculate dose rates to the thyroids of people who live near such facilities. These calculated dose rates have large uncertainty factors associated with them due to the complexity of predicting the movement of iodine-131 through the environment. This paper describes an effort to monitor iodine-131 directly in the thyroids of individuals living in the environment. A NaI(Tl)-detector system was assembled in the back of a truck for rapid and convenient measurements of members of the general public. The monitoring system has a minimum detectable activity for thyroid-bound iodine-131 of approx. 35 pCi which is sensitive enough to satisfy all legal requirements for environmental monitoring in the U.S.A. except for the child who receives iodine-131 continuously from a nuclear-power plant. Thyroid doses are calculated with more certainty from *in vivo* measurements than from measurements made on environmental and effluent samples.

INTRODUCTION

MONITORING of iodine-131 released to the environment generally involves air sampling and, when feasible, milk sampling. The primary concern with the release of iodine-131 is the potential deposition of this radionuclide in the human thyroid. If iodine-131 is delivered to the thyroid continuously, the dose rate to the thyroid is calculated by:

$$R = \frac{18.7 E q_c}{m}, \qquad (1)$$

where: R = dose rate to the thyroid (mrad/yr)
q_c = continuous thyroid burden (pCi)
E = effective energy per disintegration (MeV/dis)
m = mass of the thyroid (g).

If iodine-131 is delivered to the thyroid in a single, short-term exposure, the activity in the thyroid will decrease exponentially. The total dose received from a single exposure is calculated by:

$$D = \frac{18.7 E q_0}{m \lambda_e}(1 - e^{-\lambda_e t}), \qquad (2)$$

where: D = dose to the thyroid (mrad)
q_0 = initial thyroid burden (pCi)
t = time since the initial thyroid burden was received (yr)
λ_e = effective decay constant = 33.3 yr^{-1} based on an effective half life of 7.6 days(1)
E and m are defined previously.

Table 1 shows the continuous and single thyroid burdens of iodine-131 that will deliver the maximum permissible dose rate to the thyroid for occupational workers and members of the general public.

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TABLE 1. Relationship between dose rate to the thyroid and the associated activity of thyroid-bound iodine-131

				Maximum permissible dose rate		Thyroid burden to give max. per. dose yr	
Type of person	Source of Iodine-131	Mass of thyroid (g)*	Effective energy $\left(\frac{\text{MeV}}{\text{dis}}\right)^{\dagger}$	$\left(\frac{\text{mrad}}{\text{yr}}\right)$	Legal reference§	Continuous burden (pCi)	Single burden (pCi)
Occupational worker	Occupational	16	0.23	12,000	10 CFR 20	44,600‖	372,000‖
General public—adult maximum exposure	All but nuclear power	16	0.23	500	10 CFR 20	1,860	61,900
General public—adult average exposure	All but nuclear power	16	0.23	170	10 CFR 20	635	21,100
General public—child	All but nuclear power	2‡	0.21‡	170	10 CFR 20	87	2,880
General public—adult	Nuclear power	16	0.23	15	10 CFR 50 Appendix I	56	1,860
General public—child	Nuclear power	2‡	0.21‡	15	10 CFR 50 Appendix I	8	254

* Ref. 2 for adults.

† Ref. 3.

‡ Appendix I-10 CFR 50 assumes the child has a 2-g thyroid. Due to the samaller dimensions of a 2-g thyroid the effective absorbed energy is less by 0.02. This decrease is primarily due to the decrease in the gamma-ray dose component, as less thyroid tissue is traversed by the iodine-131 gamma rays.

§ Legal references are Title 10 of the U.S.A. Code of Federal Regulations, Parts 20 and 50. Dose equivalent values are given in these references in units of mrem/yr with an assumed quality factor of unity.

‖ Since 10 CFR 20 does not specify a maximum allowable dose equivalent for the thyroid, calculated thyroid burdens are based on the whole-body limit of 3,000 mrem per quarter for occupational workers.

Sources of iodine-131 include fallout from atmospheric nuclear-weapons tests and releases from nuclear facilities such as nuclear-power plants, hositals and laboratories. Figure 1 shows the two major pathways, inhalation of air and ingestion of milk, through which iodine-131 can be transmitted from a typical source to the thyroid of an individual. Also shown in Fig. 1 are the four locations along the pathways where measurements of iodine-131 can be made and used to calculate thyroid doses. Transfer coefficients and an estimate of the uncertainty factors associated with each coefficient are shown along the air and milk pathways.

When measurements for iodine-131 have been made at the source or in the environment in samples of air or milk, further calculations and assumptions must be made before an estimation of a corresponding dose rate to a thyroid can be reported. Because of the relatively large uncertainty factor associated with each transfer coefficient in the air and milk pathways shown in Fig. 1, a large total uncertainty exists in the final estimation of iodine-131 that reaches the general public. For example, if iodine-131 is detected in a milk sample, the uncertainty associated with the calculated dose rate to an individual's thyroid is determined by progagating the uncertainty factors shown in Fig. 1 along the ingestion pathway from MILK to THYROID; $\sqrt{2^2+2^2+1.5^2+1.5^2}=3.5$.* Thus, the actual dose rate to the thyroid could be as much as 3.5 times larger than the calculated dose rate or as little as one-third of the calculated value. Similarly, if iodine-131 is detected in an air

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* Several statistical methods exist for propagating uncertainty factors. The authors believe, for the pathways shown in Fig. 1, that the method of quadrature produces the most realistic propagated uncertainties.

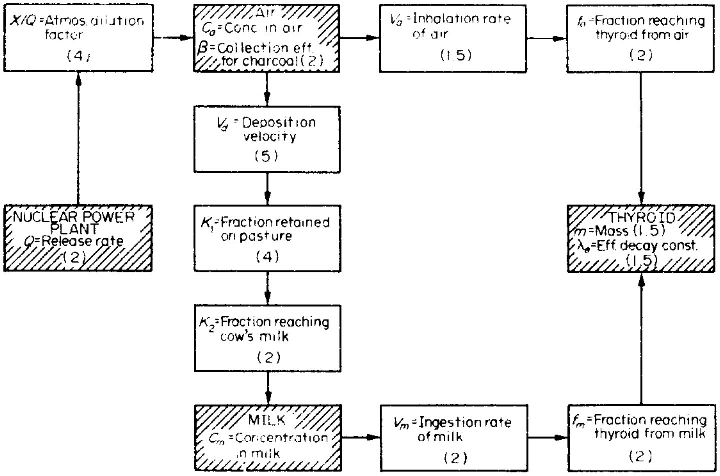

FIG. 1. Air and milk routes from a typical source of iodine-131 (nuclear-power plant) to a typical thyroid gland. Estimated uncertainty factors are shown in parenthesis for each transfer coefficient. For example, if a transfer coefficient has a mean value of Γ with an uncertainty factor of γ, then actual values for the transfer coefficient are observed to range from $\gamma\Gamma$ to Γ/γ. Although specific values for these uncertainty factors are difficult to find in the literature, the authors believe the values shown are realistic. Shaded boxes indicate where direct measurements for iodine-131 can be made.

sample, the uncertainty factor associated with a calculated dose rate to an individual's thyroid is about 3.8 for the air-thyroid pathway and about 7.8 for the air–milk–thyroid pathway.

Direct measurements for iodine-131 can be made where gaseous wastes are discharged from a source to the environment as indicated in Fig. 1. These measurements, when multiplied by the atmospheric dilution factor, are used to calculate air concentrations of iodine-131. The calculated air concentrations are used to calculate thyroid doses from inhalation of air and ingestion of milk. These calculated thyroid doses have the same uncertainties associated with the calculated doses based on direct measurements of air and milk with additional uncertainties from the release rate and the atmospheric dilution factor. The total uncertainty associated with a calculated thyroid dose based on a measurement of iodine-131 at a source is about 5.6 for the air-inhalation route and about 8.8 for the milk-ingestion route.

Much of the uncertainty associated with a calculated dose to a thyroid based on air, milk and effluent measurements can be eliminated by direct, *in vivo* monitoring of a thyroid. The objective of our work was to determine the feasibility and sensitivity of *in vivo* monitoring of the thyroid for iodine-131 at or below the limit set in Appendix I to 10 CFR Part 50. This is the most stringent legal limit set in the United States and probably in the world. A detailed description of the equipment and procedures used is available.$^{(4)}$

PROCEDURE

Instrumentation

Measurement of iodine-131 activity within a thyroid is made with a pair of 7.62-cm-dia. by 4.45-cm-thick NaI(Tl) crystals positioned above the neck between the clavicle and the thyroid cartilage (Adam's apple). The detectors are aligned as shown in Fig. 2.

Each detector is sheathed in a 0.64-cm-thick lead cylinder, which typically decreases the background count rate in the primary iodine-131 photopeak region (0.364 MeV) to 50% of the unshielded count rate. Additional shadow shielding is effected by the placement of standard lead bricks under the detectors in the plane of the mounting baseplate. The detectors and lead housing are mounted in

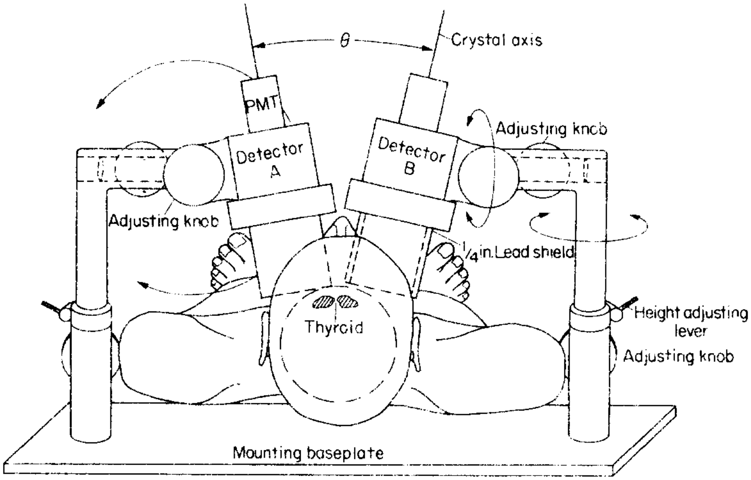

FIG. 2. Detector mounting for the mobile thyroid-monitoring system.

aluminum collars which are connected to the steel elbows shown in Fig. 2. The lead bricks are not shown.

Each detector is connected to a separate preamplifier/amplifier/discriminator (PAD) module and then connected, in parallel, to a 256-channel pluse-height analyzer. This procedure allows separate PAD adjustments to compensate for individual gain shifts in each detector. The output of the combined detectors is monitored on an oscilloscope throughout the entire counting procedure. A Teletype is used to produce a permanent copy of each gamma-ray spectrum.

The electronic components and lead shielding weigh approximately 700 kg. The equipment is easily carried and used in the back of a medium-size panel truck. This permits *in vivo* thyroid measurements to be made conveniently at the homes of members of the general public as part of routine environmental surveillance programs.

The total cost for the mobile thyroid monitoring system is approx. $7,000.

Calibration

The average adult thyroid is assumed to have a height of 5 cm, a breadth of 6 cm, a thickness (each lobe) of 1.5 cm, and a mass of 16 g.(5) The depth (center of one lobe to the surface of the skin) is assumed to be 2.3 cm.(6) A neck phantom was constructed to approximate this geometry. The phantom consisted of a polyethylene cylinder filled with water to approximate neck tissue. Two 5-ml glass ampoules, each containing a calibrated activity of iodine-131, were used to simulate the two lobes of a thyroid. A second neck phantom, with dimensions about two-thirds those of the first, was constructed to approximate the geometry of a child's neck. The depth of the thyroid in a child's neck is assumed to be 1.6 cm.(6) Counting efficiencies were measured with the adult and child phantoms for various detector positions and mock-thyroid depths. Figure 3 shows the effect of thyroid depth, measured from the center of one ampoule to the outside surface of the neck phantom, on the counting efficiency for both an adult and a

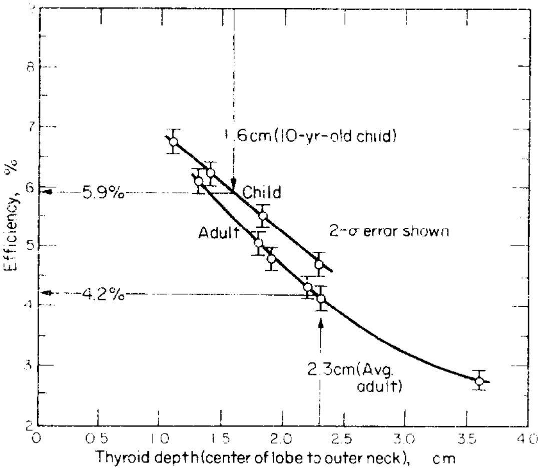

FIG. 3. Iodine-131 counting efficiency as a function of thyroid depth.

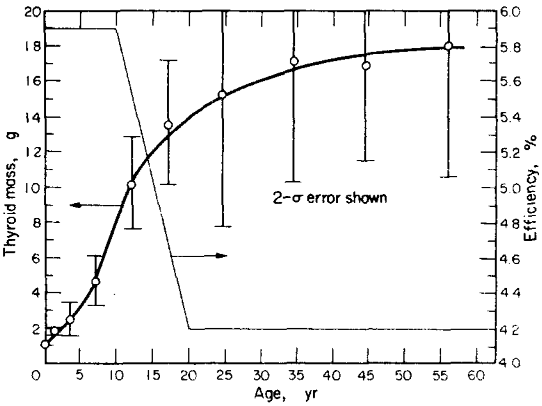

FIG. 4. Thyroid mass[7] and iodine-131 counting efficiency as a function of age.

child. For a thyroid depth of 2.3 cm for the average adult, the counting efficiency was found to be 4.2%. For a thyroid depth of 1.6 cm for the average 10-yr-old child, the counting efficiency was found to be 5.9%.

The error bars shown in Fig. 3 represent the combination of the counting error (small due to the relatively high activity of the mock thyroid) and the error associated with the positioning of the detectors. The positioning error was determined by repetitive positioning of the detectors for the same geometry and by incorporating the resulting error into the variance of the observed count rate.

An age-dependent parameter required to calculate a thyroid dose based on a measured activity of iodine-131 in the thyroid is the mass of the organ. Data are available that show the increase in thyroid mass as a function of age.[7] Figure 4 shows the relationship of both the mass of the thyroid and the counting efficiency to the age of a standard person. It is assumed that the counting efficiency varies linearly from 5.9% for a 10-yr-old child to 4.2% for a 20-yr-old adult.

Sensitivity

The analysis of each gamma-ray spectrum utilizes the 5 channels centered about the 0.364-MeV photopeak (channels 34–38, corresponding to 0.34–0.38 MeV). The time required to analyze each gamma-ray spectrum by the Compton continuum subtraction method is approximately 5 minutes. Thus, the measured iodine-131 thyroid burden can be reported to each person counted before he leaves the truck.

The minimum detectable activity (MDA) depends on the thyroid counting time, the background counting time, the background count rate, the Compton count rate, the counting efficiency, and the confidence level desired. The MDA, in units of pCi, is calculated from:

$$\mathrm{MDA} = \frac{\tau\sqrt{r/t_s + b/t_b + c/t_s}}{e2.22}, \tag{3}$$

where τ = relative error ($\tau = 1.96$ at the 95% confidence level)
r = minimum detectable count rate of iodine-131 plus contributing count rates from background and the Compton continuum from iodine-131 (cpm)
b = background count rate (cpm)
c = Compton count rate from iodine-131 with background subtracted (cpm)
t_s = thyroid counting time (min)
t_b = background counting time (min)
e = counting efficiency
2.22 = conversion factor (dpm/pCi).

Figure 5 shows a graph of MDA as a function of thyroid counting time for the measurement parameters specified. As can be seen in

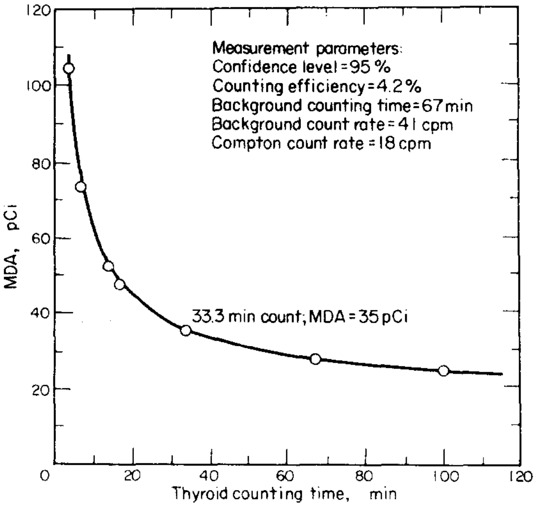

FIG. 5. Minimum detectable activity as a function of thyroid counting time.

Fig. 5, a point of diminishing returns is reached in the vicinity of a 30-min counting time. For environmental monitoring of thyroids of members of the general public, a 33.3-min (2000-sec) counting time is used since it is a reasonable length of time for the person being counted to endure, and the corresponding MDA of approx. 35 pCi is acceptable. It would be preferable if the MDA were 1/4 of this activity since the continuous thyroid burden which would deliver a dose of 15 mrad to a child's thyroid in one year is 8 pCi as shown in Table 1. However, reference to Fig. 5 shows this to be an unrealistic, perhaps impossible, achievement with the present thyroid-monitoring system due to the long counting time required.

Uncertainty of calculated dose

If iodine-131 is detected in an individual's thyroid from an *in vivo* measurement, an estimate must be made of the uncertainty associated with the corresponding calculated dose to the thyroid. If a continuous thyroid burden is observed after several *in vivo* measurements, the dose rate to the thyroid is calculated from equation (1). The mass, m, has an estimated uncertainty factor of 1.5 from Fig. 1. The measured thyroid activity, q_c, has an uncertainty from the count rate measured and from the counting efficiency, e, used in equation (3). Since the exact depth of the thyroid is not known for a given individual, variations from the average depths shown in Fig. 3 will cause variations in the counting efficiency. The total uncertainty factor associated with q_c is estimated to be 1.5. Thus, the propagated uncertainty factor associated with the calculated dose rate, R in equation (1), is about 2.1.

If iodine-131 is delivered to the thyroid in a single, short-term exposure, the total dose to the thyroid is calculated from equation (2). The thyroid mass, m, and the measured activity, q_0, each has an uncertainty factor of 1.5. The effective decay constant, λ_e, also has an uncertainty factor of 1.5 from Fig. 1. If only a single *in vivo* measurement is made, the propagated uncertainty factor associated with the calculated total dose, D in equation (2), is about 2.6. If several *in vivo* measurements are made following a single, short-term exposure to iodine-131, the actual value of λ_e for the individual being studied can be determined with little uncertainty. Thus, the propagated uncertainty factor associated with the calculated total dose is about 2.1.

EXPERIMENTAL RESULTS

As a pilot effort to determine the acceptability of the mobile thyroid-monitoring system by members of the general public, a dairy farm family living near a nuclear-power plant was counted during the summer of 1974. The results, given in Table 2, show no detectable iodine-131 in the thyroid of any member of the family. The family was enthusiastic about being counted.

The mobile thyroid-monitoring system measures iodine-131 activity, in units of picocuries, present in the thyroid. To convert a measured activity to a dose rate (e.g. mrad/yr), requires knowledge of the history of the iodine-131 in the thyroid. For example, the husband was found to have <40 pCi of iodine-131 in his thyroid. If he maintained a continuous activity of 40 pCi throughout the year, Table 2 shows that his thyroid would receive 11 mrad/yr. However, if he had received a single thyroid burden of 40 pCi of iodine-131 just before the thyroid measurement was made, then the dose to his thyroid would be 0.3 mrad. If this represented his only uptake of iodine-131 throughout the year, then his thyroid would receive 0.3 mrad/yr. If he were being measured quarterly, then the 40 pCi could represent the residual from a single thyroid burden of 165,000 pCi received just after his last quarterly measurement. This activity would have delivered 1,300 mrad to his thyroid during the quarter of a year between measurements, or an annual dose rate of 5,200 mrad/yr as shown in Table 2. Table 2 shows similar possible dose rates for the other three family members measured.

CONCLUSION

The objective of this project was to determine the feasibility and sensitivity of *in vivo* monitoring of the thyroid for iodine-131 at or

TABLE 2. Activities, and corresponding dose rates, of iodine-131 in the thyroids of residents of a dairy farm located near a nuclear-power plant

					Thyroid dose rates corresponding to measured iodine-131 activity in the thyroid from a:		
Person	Counting efficiency† (%)	Iodine-131 activity in the thyroid* (pCi)	Effective energy $\left(\frac{\text{MeV}}{\text{dis}}\right)$	Thyroid mass† (g)	Continuous burden‡ (mrad/yr)	Single annual burden§ (mrad/yr)	Single quarterly burden‖ (mrad/yr)
Husband	4.2	<40	0.23	16	<11	<0.3	<5,300
Wife	4.2	<40	0.23	16	<11	<0.3	<5,300
Daughter, age 7	5.9	<39	0.21	4	<38	<1.2	<18,900
Daughter, age 8	5.9	<39	0.21	4	<38	<1.2	<18,900

* Counting time for background and people was 33.3 min. Background count rate was 41 cpm.

† Values interpolated from Fig. 4.

‡ Calculated from equation (1). Assumes each person maintained a countinous burden of iodine-131 at the measured level throughout the year.

§ Calculated from equation (2). Assumes each person received a single burden of iodine-131 at the measured level one time during a year. The single burden is assumed to have been received just before the thyroid measurement was made.

‖ Calculated from equation (2). Assumes each person received a single burden of iodine–131 four times during a year. The single burden is assumed to have been received just after each thyroid measurement was made four times during the year.

below the limit set in Appendix I-10 CFR 50. Under normal counting conditions, the mobile thyroid-monitoring system can detect about 35 pCi in a thyroid. Table 1 shows that this activity is too high to satisfy the legal requirement for the child who receives iodine-131 continuously from a nuclear-power plant. However, the mobile thyroid-monitoring system is sensitive enough to satisfy all other legal requirements in the United States provided that measurements are made soon enough after a single exposure.

In vivo thyroid measurements provide data on real people as opposed to air, milk and effluent measurements which must be extrapolated to people. Thyroid doses are calculated with smaller uncertainty factors from *in vivo* measurements (2.1–2.6) than from air (3.8–7.8), milk (3.5), or effluent (5.6–8.8) measurements.

The mobile thyroid-monitoring system can be easily and quickly moved to a desired location for *in vivo* measurements. If the system were used routinely, the cost for each person measured would be about $30.

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