Serum triiodothyronine determination in clinical use

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SYNOPSIS Two radioimmunoassays for the determination of serum triiodothyronine (T₃) were developed. The assay of T₃ in unextracted serum had several advantages over the assay on extracted serum and was chosen for the routine determination of T₃ in serum from 117 patients requiring assessment of their thyroid status.

In 53 subjects considered retrospectively not to have thyroid dysfunction nor to have been on steroid contraceptives or therapy, the pooled mean serum T₃ concentration was 1.92 (actual range 0.88-2.62) nmol/l. A significant inverse relationship was observed between the serum T₃ level and the age of the subject. Serum total T₄ levels discriminate clearly between hypo-, eu-, and hyperthyroid patients and provide a rather more sensitive index of hyperthyroid function than total serum T₄. In the face of normal serum T₄, the T₃ level was depressed in five patients with marked hypoproteinaemia and elevated in two patients taking heroin.

The application of radioimmunological methods to the measurement of serum triiodothyronine (T₃) in health and disease has revealed a previously unsuspected role for this hormone in the maintenance of the euthyroid state. Clinically, serum T₃ estimations have been advocated for detecting early hyperthyrotoxicosis (Hollander et al, 1971b) and have revealed a new variant of hyperthyroidism, 'T₃-toxicosis', in which patients diagnosed unequivocally as thyrotoxicosis have normal serum thyroxine (T₄) levels but increased concentrations of T₃ (Sterling et al, 1970). In addition it is now clear that treatment of hyperthyroidism, by surgery or with drugs, leads to preferential serum T₃ production (Bellabarba and Tremblay, 1972) as do low iodine diets (Hollander et al, 1971a).

The accuracy of methods based on protein-binding techniques for T₃ analysis has been impaired by interference from in vivo T₃-binding proteins, in particular thyroid hormone-binding globulin (TBG). When interference from this source has gone unrecognized high serum values for T₃ have been reported (Gharib et al, 1970).

Several reagents capable of blocking plasma protein T₃-binding sites have been reported and these include T₄ (Chopra et al, 1971), tetrachlorothyronine (Mitsuma et al, 1971), diphenylhydantoin (Liebling and Utiger, 1972), salicylate (Larsen, 1971), and 3-aminophosphalene-sulphonic acid (Mitsuma et al, 1972). Each has drawbacks; either they are unstable in solution or they interfere with the antigen-antibody reaction (Hüfner and Hesch, 1973a). Recently, sodium ethylmercurithiosalicylate (Merthiolate, thiomersal) has been shown to inhibit the binding of T₃ to thyroxine-binding proteins (Bellabarba and Tremblay, 1973), and this reagent has been incorporated into radioimmunoassays for triiodothyronine (Hüfner and Hesch, 1973b; Kirkegaard et al, 1974). In the presence of serum proteins, merthiolate does not influence the antibody-hapten reaction (Kanagasababathy and Wellby, 1974).

This report describes a comparison of two radioimmunoassays for serum T₃, the alcoholic extraction assay being used as a reference method for the assay on unextracted serum. Merthiolate was used to block the TBG binding sites. A preliminary clinical evaluation of the results on patients for whom routine in vitro thyroid function tests have been requested is presented.

Material and Methods

BARBITONE-ALBUMIN-MERTHIOLATE BUFFER Barbitone buffer (0.1 mol/l) at pH 8-65 contained merthiolate (sodium ethylmercurithiosalicylate, 5-00 mmol/l) and bovine albumin (5 g/l). All solutions were stored at 4°C unless otherwise stated.
LABELLED TRIIODOTHYRONINE
High specific activity $^{125}$I-T$_3$ (ca 400 mCi/mg) in 50% propylene glycol was purchased from Abbott Laboratories and further purification was found to be unnecessary. It was diluted to about 500 pmol/l with barbitone-albumin-Merthiolate buffer.

STANDARDS
L-3', 3, 5-triiodothyronine (B grade) was obtained from Calbiochem Ltd, and its molar extinction coefficient (Gemmill, 1955) in sodium hydroxide (40 mmol/l) was used as an index of purity. Further purification proved to be unnecessary. A stock standard solution (768 μmol/l) was prepared in acidified ethanol (10 ml HCl/l) and stored at −20°C. Standard T$_3$ was prepared by diluting the stock standard solution 125 times with sodium hydroxide (40 mmol/l). A 50 μl aliquot of this solution was diluted to 10 ml with T$_3$-free serum or with 67% ethanol, and these working standards were stored in small aliquots at −20°C.

Assay standards were prepared immediately before the assay by doubling dilutions of working standard in T$_3$-free serum or 67% ethanol to give from 768 to 24 fmol of T$_3$ per assay tube.

TRIIODOTHYRONINE-FREE SERUM
Five grams of Norit A charcoal (Sigma) were added to 50 ml of pooled, human sera (visibly free from haemolysis and icterus) and gently stirred for one hour at room temperature. After centrifugation a further 4 g were added and the process was repeated. Finally the supernatant was passed through millipore filters (Sartorius Membrane filter SM 11306, 0.45 μm) and stored at −20°C. More than 99% of added $^{125}$I-T$_3$ was removed by this procedure.

ANTISERUM
The antiserum (No. 5303), raised in sheep against a triiodothyronine-albumin conjugate, was kindly donated by Professor R. P. Ekins (Institute of Nuclear Medicine, The Middlesex Hospital, London). Small volumes were stored at −20°C, thawed when required, and diluted to 1:1400 with barbitone-albumin-Merthiolate buffer.

CHARCOAL SUSPENSION
For the assay of T$_3$ in unextracted serum an 8 g/l suspension of Norit A charcoal in barbitone buffer was used. Assays carried out in 67% ethanol required the charcoal to be coated with Dextran T$_{70}$ (0.5 g/l) for the optimal separation of free and antibody-bound T$_3$.

PATIENTS AND PREPARATION OF SAMPLES
Thyroid function tests were requested on 117 patients seen by general practitioners. Blood was obtained by venepuncture from these outpatients and allowed to clot, and the serum was separated by centrifugation. The samples were stored at −20°C. In some experiments alcoholic extracts of serum were prepared by the addition of two volumes of ice-cold ethanol and spinning down the precipitated proteins. Recovery of added $^{125}$I-T$_3$ under these conditions was 100% and confirms the results of Patel and Burger (1973). Duplicate 50 μl aliquots of the supernatant were used directly in the radioimmunoassay.

Thyroxine was measured by the Abbott Tetrasorb procedure controlled as previously described (Watson and Lees, 1973). Sera showing T$_4$ levels that were close to upper or lower normal limits were assayed for ‘free thyroxine index’ (FTI). The latter was calculated as total T$_4$ divided by the unsaturated thyroid hormone-binding globulin level, expressed as a fraction of a laboratory pooled serum standard and measured by the Thyopac-3 test (Radiochemical Centre).

Radioimmunoassay
To 50 μl of the unknowns, standards, and ‘zero’ standards were added 100 μl of $^{125}$I-T$_3$ solution and 100 μl of diluted antiserum. For the unknowns and ‘zero’ standard a similar set of tubes was set up containing buffer instead of antiserum (blanks). After mixing and incubation overnight at 4°C or for one hour at 37°C, the tubes were equilibrated in an ice bath. A 500 μl aliquot of a well-stirred charcoal suspension at 2°C was forcibly added to each tube with the aid of an automatic syringe pipette. After incubation for 20 minutes the tubes were centrifuged at 4000 rev/min for 10 minutes and returned to the ice bath. The supernatants were removed by suction and the charcoal pellets counted in an LKB Wallac 8000 gamma counter for at least 60 seconds (ie, about 10$^4$ counts).

CALCULATIONS
All counts were automatically corrected for background.

Standards
The reciprocal of B, the fraction of T$_3$ bound by the antibody, was calculated by the formula:

$$\frac{1}{B} = \frac{F_0}{F_0 - F_u}$$

where B is the fraction bound, $F_0$ is the number of counts adsorbed by the charcoal in the blank, ie, in the absence of antiserum, and $F_u$ is the number of
counts adsorbed by the charcoal in each standard tube in the presence of antiserum. This was plotted against the amount of cold T₃ in each standard tube, and a reproducible linear relationship was found over the range 0-768 fmol T₃, corresponding to serum concentrations from zero to about 15 nmol/l.

**Unknowns**

Preliminary experiments indicated that the adsorption of free T₃ onto charcoal varied from serum to serum and it was found necessary to run a blank with each sample for accurate results. The reciprocal of the fraction bound was calculated as for the standards. The serum T₃ content was derived from the standard curve, corrected for any dilution and expressed as nmol/l.

**Statistics**

The mean, standard deviation, and correlation and regression coefficients were calculated according to Snedecor and Cochran (1956) on a programmable desk-top calculator.

**Results**

**Sensitivity**

Cross-reaction of the antisera with thyroxine (T₄), triiodothyroacetic acid, and triiodothyroacetic acid was less than 0·1% in each case. Doubling dilutions of the sera from thyrotoxic and euthyroid patients with T₃-free serum resulted in curves that did not differ significantly from the standard curve.

**Recovery Experiments**

Recovery was determined by comparing the amount of T₃ detected by radioimmunoassay (y) with the known quantities (up to 600 fmol T₃) added to hypo-, eu-, and hyper-thyroid sera (x). For the assay on alcoholic extracts the relationship was given by the equation y = 1.02x + 4.72 (x and y units in fmol, r = 0.987, n = 16, and p < 0.001). For the unextracted serum assay the line was given by y = 1.02x – 1.08 (r = 0.980, n = 28, p < 0.001). When the same sample was analysed by both methods the amount found in the unextracted serum (y) was highly correlated with the level detected by the alcoholic extraction assay (x) and the relationship was described by the equation y = 1.05x – 0.02 (r = 0.973, n = 31, p < 0.001). The result confirms the ability of Merthiolate to block the T₃-binding sites of serum thyroxine-binding globulin. The incubation time could be reduced to one hour at 37°C without loss of accuracy or sensitivity. The estimate at 37°C (y) was related to the value at 4°C (x) by the equation y = 1.02x + 0.03 (r = 0.984, n = 18, p < 0.001).

**Sensitivity and Reproducibility**

For the assay on unextracted serum samples these statistics have been summarized in table I. The between-batch coefficient of variation for six assays was 8·6%. The coefficient of variation within-batch ranged from 14% in the hypothyroid group to 3% in the euthyroid group. Very similar figures were calculated for the alcoholic extraction assay with the exception that ethanol tended to depress the binding in the low dose region of the standard curve (intercept 1/B was 1.887 ± 0.092, n = 10). A direct result of this effect was a reduction in the assay sensitivity (smallest detectable dose 11 ± 6 fmol).

**Normal Range**

The normal range (mean ± 2 SD) of serum T₃ in 53 euthyroid outpatients was 1·92 ± 0·77 nmol/l (1·25 ± 0·50 μg/l). This agrees well with values found by most other investigators using radio-

<table>
<thead>
<tr>
<th>Standard Curve</th>
<th>Between-batch Variation</th>
<th>Within-batch Variation</th>
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<tbody>
<tr>
<td>Intercept 1/B</td>
<td>1·582 ± 0·109</td>
<td>1·582 ± 0·025</td>
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<tr>
<td>Inverse slope (pmol)</td>
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<tr>
<td>Correlation coefficient</td>
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<td>Smallest detectable dose (fmol)</td>
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<td>50% of intercept (pmol)</td>
<td>0·293 ± 0·043</td>
<td>0·293 ± 0·018</td>
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<tr>
<td>Charcoal adsorption %</td>
<td>95·32 ± 0·47</td>
<td>95·32 ± 0·68</td>
</tr>
<tr>
<td>Control serum (nmol/l)</td>
<td>2·048 ± 0·176</td>
<td>2·048 ± 0·156</td>
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<tr>
<td>Samples</td>
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<tr>
<td>&lt; 0·75 nmol/l</td>
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<td>0·512 ± 0·072</td>
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<tr>
<td>0·75 &lt; 2·25 nmol/l</td>
<td>2·081 ± 0·063 (78)</td>
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<tr>
<td>&gt; 2·25 nmol/l</td>
<td>4·075 ± 0·145 (35)</td>
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<tr>
<td>Charcoal adsorption</td>
<td>94·64 ± 0·92</td>
<td>94·64 ± 0·90</td>
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</table>

*Calculated from unweighted regression analysis, mean ± SD
†SD of zero dose/slope at this point × √2 (Ekins et al, 1968)
‡Control serum at beginning and end of each run
§Calculated by the duplicates method (Snedecor and Cochran, 1956)
±Number of duplicates.
immunoassay but different TGB blocking agents. A small but consistent fall in serum T3 with increasing age was observed in the present study (figure) and confirms the earlier observations of Brunelle and Bohun (1972) and Rubenstein et al (1973).

Clinical Results

Summarized in table II are the serum T3 and T4 levels in 117 unselected patients for whom in vitro thyroid function tests were requested. The biochemical data were compared with the retrospective assessment of a patient's thyroid status, and the final assessment was based on the outcome of examination, consultant opinion, and all investigations.

The salient features are as follows. All 38 hyperthyroid patients had high serum T4 concentrations although increased serum levels of thyroxine were observed in only 31 patients. Of the remainder with normal serum T4 concentrations, four were clinically diagnosed as 'early' thyrotoxicosis, one as 'recurrent' thyrotoxicosis while two were initially correctly diagnosed as 'T3-toxicosis'. Four of the five neomerczazole-treated thyrotoxics had increased serum T3 levels but normal or low serum T4 concentrations. Low serum levels of T3 and T4 were observed in all seven cases of overt myxoedema. One patient had a border-line low serum T4 level but a normal serum T3 concentration. The serum FTI was normal and the initial clinical diagnosis of hypothyroidism not supported. Low serum T3 levels were found in all five patients with hypoproteinaemia from various causes. However, serum T4 levels and the free thyroxine index were normal in every case. Two subjects, who admitted taking heroin, had raised serum T3 concentrations (3-4 and 3-6 nmol/l) but normal serum T4 levels (122 and 133 nmol/l) and normal FTI (7-5 and 8-4).

Discussion

A radioimmunoassay for the direct measurement of T3 in serum has been described and its performance compared with an alcoholic extraction assay. For routine use the direct assay was preferred, primarily because the time for antibody incubation could be reduced to one hour at 37°C and fewer pipetting steps were involved. Thus results could be obtained on the same working day with fewer potential sources

<table>
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<tr>
<th>Final Assessment</th>
<th>T3</th>
<th>T4</th>
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<tbody>
<tr>
<td></td>
<td>Low*</td>
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<tr>
<td>Hypothyroid</td>
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<td>Hypoproteinaemic</td>
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<td>T4-treated hypothyroids</td>
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<td>Euthyroid</td>
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<td>Pregnant euthyroid</td>
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<td>Clinically euthyroid heroin users</td>
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</tr>
<tr>
<td>Hypothyroid</td>
<td>(31)</td>
<td></td>
</tr>
<tr>
<td>Neomerczazole treated hyperthyroid</td>
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</tr>
<tr>
<td>Thyroidectomized hyperthyroid on T4</td>
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<td></td>
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</table>

Table II Serum T3 and T4 levels in 117 patients for whom thyroid function tests were required

*Less than 2SD below the mean. Normal range for T4 is 73 to 163 nmol/l
bGreater than 2SD above the mean
cTotal number of cases in each group
dNumber of cases in each subgroup

*Same patient.
of error. In terms of accuracy the direct assay overestimated the T₃ content on average by some 5%. This value agrees well with the 95% efficacy of Merthiolate in displacing T₃ from TBG binding sites reported by Hüfner and Hesch (1973a) and Kirkegaard et al (1974).

A disturbing feature of the radioimmunological measurement of T₃ in unextracted serum is the occurrence of low values in patients with hypoproteinæmia as a result of nephrotic syndrome, coeliac disease or senile malabsorption. Low serum T₃ levels have also been detected in kwashiorkor. However, in the latter case this observation appears to be due to a methodological artefact, since no low T₃ values were observed when sufficient T₃-free normal serum was added to the immunoassay tube to make the serum protein level comparable to normal serum samples (van der Westhuizen, 1973). Thus before any reliance can be placed on serum T₃ data from hypoproteinæmic patients it is essential that the immunoassay system be shown to be unaffected by large changes in serum protein levels. Further work is needed to elucidate this phenomenon. However, normal patient to patient variation in total serum protein content does not appear to affect the accuracy of the method significantly, and in practice it is the high serum T₃ values that are of clinical importance.

Published ranges for euthyroid levels of serum T₃ as determined by radioimunoassay vary considerably, although workers have agreed that the mean lies between 1.5 and 2.3 nmol/l with a standard deviation of some 0.3 to 0.5 nmol/l. This interlaboratory variation could be due to methodological differences since the apparent serum T₃ concentration depends to some extent upon the blocking agent used (Hüfner and Hesch, 1973a), but diet and age of the control group may also be important. Provided that the correct normal ranges are established for each area laboratory, small dietary differences should not affect clinical conclusions based on the radioimmunoassay data. However, the age distribution of the population studied might do so.

If the normal population confidence limits derived from a least squares regression analysis of serum T₃ level on patient's age are compared with those of the pooled data then areas can be identified where younger patients may be misclassified as early thyrotoxicosis and older patients wrongly considered to be euthyroid (figure). However, more data are required before the diagnostic value of this refinement of the normal range can be assessed. No age-dependent changes in serum T₄ concentration were observed in the present study. In a much larger group of euthyroid patients, a small but significant decrease in serum T₄ levels was observed in patients over 65 years of age (Herrmann et al, 1974). The authors concluded that reduced protein-binding of thyroid hormones, particularly T₃, could be excluded as the cause of low serum T₃ and T₄ concentrations observed in aged patients.

At the present time the usefulness of serum T₃ measurements in the routine diagnosis of thyroid disease is restricted to two well-defined areas. Where the clinical pattern indicates hyperthyroidism, but serum T₄ level and the FTI are normal, measurement of serum T₃ concentrations can confirm 'T₃-toxicosis', and seven such patients were identified in the present series. Of these seven patients, four were diagnosed as 'early thyrotoxicosis'. The ability to provide biochemical support for this diagnosis is of great value and suggests that all patients for whom serum T₄ estimations have been requested should also be screened for serum T₃. An increased serum T₃ level relative to the T₄ concentration has been observed during treatment of hyperthyroidism (Bellabarba and Tremblay, 1972) and this occurred in four patients in the present study. In these cases measurement of serum T₃ levels helps to define thyroid status.

Not all cases of increased serum levels of T₃, however, appear to be associated with clinical evidence of hyperthyroidism. In this study two clinically euthyroid heroin addicts had high levels of serum T₃ but normal T₄ concentrations. Whether this reflects the pituitary-thyroid relationship seen in Pendred's syndrome (deafness and non-iodine-deficiency goitre) is not known, but Gomez-Pan et al (1974) recently reported such a patient with raised serum T₃ concentrations and normal levels of serum T₄. Interestingly an increased TSH response to thyrotropin releasing hormone (TRH) was observed in this patient. Studies in mice have shown that codeine, which has a chemical structure very similar to that of heroin, enhances the TSH response to TRH (Redding et al, 1966). While caution must be exercised in drawing inferences from animal studies and applying them to the human it remains a possibility that heroin was having a similar effect in the patients addicted to this drug. However, in a series of clinically euthyroid heroin addicts studied by Webster et al (1973) an increased mean serum T₄ level was observed as a result of an elevated serum TBG binding capacity. Serum T₃ levels were not measured.

In conclusion, a preliminary clinical evaluation of serum T₃ estimations in routine diagnostic use suggests that measurement of serum T₃ levels would provide more information than T₄ and should be requested in all cases of suspected hyperthyroidism and in patients undergoing therapy for thyroid disorders.
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References


Larsen, P. R. (1971). Inhibition of triiodothyronine (T3) binding to thyroxine-binding globulin by sodium salicylate and its application to immunoassay of T3 in human serum. \textit{Metabolism}, \textbf{20}, 976-980.


