Influence of thyroidectomy on thyroxine metabolism and turnover rate in rats

Hidenori Nagao1, Tetsuya Imazu1, Hiroyuki Hayashi2, Kenjo Takahashi3 and Kouichi Minato1

1Pharmacokinetics Research Department of ASKA Pharmaceutical Co., Ltd, 2Synthetic Research Department of ASKA Pharmaceutical Co., Ltd and 3ASKA Pharma Medical Co., Ltd, 5-36-1, Shimosakunobe, Takatsu-ku, Kawasaki 213-8522, Japan

(Correspondence should be addressed to K Minato; Email: minato-k@aska-pharma.co.jp)

Abstract

Little is known about the kinetics and metabolism of thyroid hormones in the hypothyroid state. To investigate these factors, we developed a reliable method for measurement of serum thyroxine (T4), triiodothyronine (T3), reverse-T3 (rT3) and stable isotope-labeled T4 ([13C9]T4), using online solid-phase extraction liquid chromatography–mass spectrometry/mass spectrometry (online SPE LC–MS/MS). We measured supply and turnover rates of T4 in thyroidectomized (Tx) rats using [13C9]T4 as a tracer. In rats, serum T4, T3 and rT3 were decreased but not completely ablated after surgical Tx. Endogenous T4 and T3 levels in Tx rats were maintained at a constant low level throughout the experimental period. [13C9]T4 levels declined with a half-life of ~1.2 days after it was administered to Tx rats intravenously. These findings strongly suggest that serum T4 levels in Tx rats are maintained by T4 supplied by extra-thyroidal tissues (e.g. secretion of extra-thyroidal storage, enhancement of enterohepatic recirculation, and production in extra-thyroidal tissues). Moreover, the turnover rate of T4 in Tx rats was approximately twofold lower than in controls. This finding suggests that degradation of serum T4 is repressed by Tx. In conclusion, serum T4 is maintained at a constant low level by T4 supply from extra-thyroidal tissues and repression of T4 degradation in Tx rats. The powerful online SPE LC–MS/MS tool can be used to investigate thyroid hormones kinetics and metabolism, and thus has the potential to be used as a diagnostic tool and to investigate the pathogenesis of thyroid disease.

Journal of Endocrinology (2011) 210, 117–123

Introduction

Thyroxine (T4) is the main secretory product of thyroid follicular epithelial cells but has low biological activity. T4 is converted to the more active triiodothyronine (T3). Approximately 80% of the T3 produced daily is formed by removal of one iodine atom from the outer ring of T4 (outer-ring deiodination) in tissues outside the thyroid gland, such as the liver, kidney, muscle, and nervous system. The deiodination reaction is catalyzed by deiodinase enzymes. Two deiodinases, type 1 and type 2, catalyze the conversion of T4 to T3. Type 3 deiodinase catalyzes the conversion of T4 to reverse T3 (rT3) and of T3 to 3,3′-diodothyronine (inner-ring deiodination) (Gereben et al. 2008); neither rT3 nor 3,3′-diodothyronine has biological activity (Bianco et al. 2002). In addition to deiodination, T4 can be metabolized to its glucuronide forms by UDP-glucuronosyltransferases (UGTs). T4 glucuronide is readily excreted in bile and is subsequently hydrolyzed by β-glucuronidases in the intestine, and may affect the enterohepatic circulation of T4 (Visser 1994). It has been reported that UGT1A1 in the intestine, and UGT1A7, UGT1A9, and UGT1A10 in the kidney mainly contribute to the T4 glucuronidation activity in humans (Yamanaka et al. 2007). The change of these activities via inhibition and induction by administered drugs (Ohnhaus & Studer 1983, Isojarvi et al. 1992, Kiang et al. 2005) as well as genetic polymorphisms (Miners et al. 2002) may be a causal factor of interindividual differences in serum T4 level.

Evans et al. (1960) reported that thyroidectomized (Tx) rats, whose growth had plateaued, could be made to grow again with a daily injection of large doses of inorganic iodide (3–5 mg/day). It has been subsequently shown that daily administration of 5 mg iodide to Tx rats partially restores their heart rate, metabolic rate, gonad and adrenal size and function, and pituitary acidophils (Evans et al. 1966). There are two potential mechanisms for this phenomenon: supply of thyroid hormones by extra-thyroidal tissues and repression of thyroid hormone degradation. Previously, T3 generation from T4 using radiolabeled T4 and T3 has been reported in detail (Silva & Matthews 1984a,b, Silva et al. 1984). However, little is known about the kinetics and metabolism of T4 in the hypothyroid state.
Although a sensitive and widely used immunoassay-based method exists for measuring serum thyroid hormones, there was a need for improved methods to investigate thyroid hormones kinetics and metabolism. Liquid chromatography–mass spectrometry/mass spectrometry (LC–MS/MS) is capable of simultaneously and accurately detecting specific chemicals in various specimens. One of the unique advantages of this method, which uses a stable isotope-labeled compound as a tracer, is that an endogenous compound and its exogenously administered labeled analog can be measured separately using LC–MS/MS (Lin et al. 2010) or GC–MS/MS (Kasuya et al. 2005). Mass spectrometry of serum samples allows safe and precise in vivo measurement using stable isotopes, and such technology has contributed to a better understanding of metabolic diseases such as diabetes mellitus (Blaak et al. 2000, Hankard et al. 2000). Stable isotope-labeled tracers are commonly used to quantify the turnover rates of various metabolic intermediates and can provide information about physiological regulation. We have synthesized labeled T₄ by region-selective labeling with carbon 13. The biological tracer was T₄ with inner ring substitution with nine stable isotopes ([13C₉]T₄). Quantification methods for endogenous and exogenous (stable isotope-labeled) thyroid hormones in animal serum using online solid-phase extraction (SPE) LC–MS/MS were developed using [2H₅]T₄ as an internal standard. After i.v. administration of [13C₉]T₄ to Tx and control rats, serum samples containing endogenous and exogenous (labeled) thyroid hormones were analyzed using the double isotope dilution method. We investigated supply and turnover rates of T₄ in Tx and control rats by the stable isotope tracer method. The present study is the first to use stable isotope tracer injection in Tx rats.

The great potential of this technology can be extended to the use of T₄ labeled with ¹³C as a diagnostic tool for investigating pathogenesis of thyroid disease. The objectives of this study were to examine the kinetics and metabolism of T₄ in the hypothyroid state using Tx rats.

Materials and Methods

Chemicals

[T₄-L-tyrosine-²H₅]HCl (Fig. 1) was purchased from IsoSciences, LLC (King of Prussia, PA, USA). T₄, T₃ (Fig. 1), and rT₃ were purchased from Sigma–Aldrich Co. All other chemicals and reagents were of the highest analytical grade commercially available.

Although a sensitive and widely used immunoassay-based method exists for measuring serum thyroid hormones, there was a need for improved methods to investigate thyroid hormones kinetics and metabolism. Liquid chromatography–mass spectrometry/mass spectrometry (LC–MS/MS) is capable of simultaneously and accurately detecting specific chemicals in various specimens. One of the unique advantages of this method, which uses a stable isotope-labeled compound as a tracer, is that an endogenous compound and its exogenously administered labeled analog can be measured separately using LC–MS/MS (Lin et al. 2010) or GC–MS/MS (Kasuya et al. 2005). Mass spectrometry of serum samples allows safe and precise in vivo measurement using stable isotopes, and such technology has contributed to a better understanding of metabolic diseases such as diabetes mellitus (Blaak et al. 2000, Hankard et al. 2000). Stable isotope-labeled tracers are commonly used to quantify the turnover rates of various metabolic intermediates and can provide information about physiological regulation. We have synthesized labeled T₄ by region-selective labeling with carbon 13. The biological tracer was T₄ with inner ring substitution with nine stable isotopes ([13C₉]T₄). Quantification methods for endogenous and exogenous (stable isotope-labeled) thyroid hormones in animal serum using online solid-phase extraction (SPE) LC–MS/MS were developed using [2H₅]T₄ as an internal standard. After i.v. administration of [13C₉]T₄ to Tx and control rats, serum samples containing endogenous and exogenous (labeled) thyroid hormones were analyzed using the double isotope dilution method. We investigated supply and turnover rates of T₄ in Tx and control rats by the stable isotope tracer method. The present study is the first to use stable isotope tracer injection in Tx rats.

The great potential of this technology can be extended to the use of T₄ labeled with ¹³C as a diagnostic tool for investigating pathogenesis of thyroid disease. The objectives of this study were to examine the kinetics and metabolism of T₄ in the hypothyroid state using Tx rats.

Materials and Methods

Chemicals

[T₄-L-tyrosine-²H₅]HCl (Fig. 1) was purchased from IsoSciences, LLC (King of Prussia, PA, USA). T₄, T₃ (Fig. 1), and rT₃ were purchased from Sigma–Aldrich Co. All other chemicals and reagents were of the highest analytical grade commercially available.

Although a sensitive and widely used immunoassay-based method exists for measuring serum thyroid hormones, there was a need for improved methods to investigate thyroid hormones kinetics and metabolism. Liquid chromatography–mass spectrometry/mass spectrometry (LC–MS/MS) is capable of simultaneously and accurately detecting specific chemicals in various specimens. One of the unique advantages of this method, which uses a stable isotope-labeled compound as a tracer, is that an endogenous compound and its exogenously administered labeled analog can be measured separately using LC–MS/MS (Lin et al. 2010) or GC–MS/MS (Kasuya et al. 2005). Mass spectrometry of serum samples allows safe and precise in vivo measurement using stable isotopes, and such technology has contributed to a better understanding of metabolic diseases such as diabetes mellitus (Blaak et al. 2000, Hankard et al. 2000). Stable isotope-labeled tracers are commonly used to quantify the turnover rates of various metabolic intermediates and can provide information about physiological regulation. We have synthesized labeled T₄ by region-selective labeling with carbon 13. The biological tracer was T₄ with inner ring substitution with nine stable isotopes ([13C₉]T₄). Quantification methods for endogenous and exogenous (stable isotope-labeled) thyroid hormones in animal serum using online solid-phase extraction (SPE) LC–MS/MS were developed using [2H₅]T₄ as an internal standard. After i.v. administration of [13C₉]T₄ to Tx and control rats, serum samples containing endogenous and exogenous (labeled) thyroid hormones were analyzed using the double isotope dilution method. We investigated supply and turnover rates of T₄ in Tx and control rats by the stable isotope tracer method. The present study is the first to use stable isotope tracer injection in Tx rats.

The great potential of this technology can be extended to the use of T₄ labeled with ¹³C as a diagnostic tool for investigating pathogenesis of thyroid disease. The objectives of this study were to examine the kinetics and metabolism of T₄ in the hypothyroid state using Tx rats.

Materials and Methods

Chemicals

[T₄-L-tyrosine-²H₅]HCl (Fig. 1) was purchased from IsoSciences, LLC (King of Prussia, PA, USA). T₄, T₃ (Fig. 1), and rT₃ were purchased from Sigma–Aldrich Co. All other chemicals and reagents were of the highest analytical grade commercially available.

Although a sensitive and widely used immunoassay-based method exists for measuring serum thyroid hormones, there was a need for improved methods to investigate thyroid hormones kinetics and metabolism. Liquid chromatography–mass spectrometry/mass spectrometry (LC–MS/MS) is capable of simultaneously and accurately detecting specific chemicals in various specimens. One of the unique advantages of this method, which uses a stable isotope-labeled compound as a tracer, is that an endogenous compound and its exogenously administered labeled analog can be measured separately using LC–MS/MS (Lin et al. 2010) or GC–MS/MS (Kasuya et al. 2005). Mass spectrometry of serum samples allows safe and precise in vivo measurement using stable isotopes, and such technology has contributed to a better understanding of metabolic diseases such as diabetes mellitus (Blaak et al. 2000, Hankard et al. 2000). Stable isotope-labeled tracers are commonly used to quantify the turnover rates of various metabolic intermediates and can provide information about physiological regulation. We have synthesized labeled T₄ by region-selective labeling with carbon 13. The biological tracer was T₄ with inner ring substitution with nine stable isotopes ([13C₉]T₄). Quantification methods for endogenous and exogenous (stable isotope-labeled) thyroid hormones in animal serum using online solid-phase extraction (SPE) LC–MS/MS were developed using [2H₅]T₄ as an internal standard. After i.v. administration of [13C₉]T₄ to Tx and control rats, serum samples containing endogenous and exogenous (labeled) thyroid hormones were analyzed using the double isotope dilution method. We investigated supply and turnover rates of T₄ in Tx and control rats by the stable isotope tracer method. The present study is the first to use stable isotope tracer injection in Tx rats.

The great potential of this technology can be extended to the use of T₄ labeled with ¹³C as a diagnostic tool for investigating pathogenesis of thyroid disease. The objectives of this study were to examine the kinetics and metabolism of T₄ in the hypothyroid state using Tx rats.
Chemical synthesis of $[^{13}C_9]T_4$

$[^{13}C_9]T_4$ was synthesized chemically from $[^{13}C_9]$ tyrosine using a modification of Salamonczyk's method (Salamonczyk et al. 1997; Fig. 2). The diiodo derivative of 1-oxaspiro[2,5]bicycloocta-4,7-dien-6-one reacted readily with $[^{13}C_9]$3,5-diiodo-L-tyrosine. In turn, the diiodo derivative of 1-oxaspiro[2,5]bicycloocta-4,7-dien-6-one was prepared by sodium bismuthate oxidation of diiodinated $p$-hydroxybenzyl alcohol derivative.

Animals

Seven-week-old male Sprague–Dawley rats were obtained from Charles River Laboratories Japan (Kanagawa, Japan). Animals were fed a commercial diet (AIN-93G, Oriental Yeast Co., Tokyo, Japan) and distilled water ad libitum. The cages were located in a light (0800–2000 h lights on), temperature (23 ± 5 °C) and humidity (60 ± 20%) controlled room.

The rats were allowed to acclimatize for 1 week before starting experiments.

All experimental procedures were approved by the Animal Research Committee of ASKA Pharmaceutical Co., in accordance with the Basic Guidelines for Proper Conduct of Animal Testing and Related Activities in the Research Institutions under the Jurisdiction of the Ministry of Health, Labour and Welfare of Japan.

Thyroidectomy

Rats were anesthetized with Isoflurane (Escain; Mylan, Pittsburgh, PA, USA). Thyroid glands were resected from the tracheal tube. After surgery, serum TSH rapidly increased and then achieved a steady state (~13·4 ± 3·6 ng/ml) after 7 days. Complete resection of the thyroid in the Tx rats

Table 1 Liquid chromatography (LC) conditions used for the online solid-phase extraction LC–mass spectrometry (MS)/MS analysis

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Flow rate (ml/min)</th>
<th>FCV-12AH valve position</th>
<th>Pump A</th>
<th>Pump B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-00</td>
<td>3·50</td>
<td>A</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>0-99</td>
<td>4-00</td>
<td>A</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>1-00</td>
<td>4·00</td>
<td>A</td>
<td>0</td>
<td>95</td>
</tr>
<tr>
<td>1-80</td>
<td>0·35</td>
<td>A</td>
<td>0</td>
<td>95</td>
</tr>
<tr>
<td>2-00</td>
<td>0·35</td>
<td>A</td>
<td>0</td>
<td>95</td>
</tr>
<tr>
<td>2-50</td>
<td>0·35</td>
<td>B</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>8-00</td>
<td>0·35</td>
<td>B</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>9-60</td>
<td>0·35</td>
<td>B</td>
<td>1</td>
<td>99</td>
</tr>
<tr>
<td>9-61</td>
<td>0·35</td>
<td>B</td>
<td>1</td>
<td>99</td>
</tr>
<tr>
<td>11-00</td>
<td>0·80</td>
<td>B</td>
<td>1</td>
<td>99</td>
</tr>
<tr>
<td>11-02</td>
<td>5·00</td>
<td>A</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>11-03</td>
<td>5·00</td>
<td>A</td>
<td>1</td>
<td>99</td>
</tr>
<tr>
<td>12-01</td>
<td>0·35</td>
<td>A</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>12-04</td>
<td>0·35</td>
<td>A</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>12-54</td>
<td>0·35</td>
<td>A</td>
<td>95</td>
<td>5</td>
</tr>
</tbody>
</table>

Valve position A, sample extraction or washing on the SPE column; valve position B, back-flush onto the analytical column and chromatographic separation; mobile phase A-1, 1·0 vol% formic acid; mobile phase A-2, 0·05 vol% acetic acid; mobile phase B, methanol; the pump C delivered 0·05 vol% acetic acid/methanol (95:5, v/v) at 0·35 ml/min to equilibrate the analytical column.

Table 2 Precision and accuracy of the intra-day assay. Data are expressed as the mean values ± s.d. (n = 5). Figures in parentheses are expressed as coefficient of variance (%)

<table>
<thead>
<tr>
<th>Concentration (ng/ml)</th>
<th>$T_4$ (mean ± s.d.)</th>
<th>$T_3$ (mean ± s.d.)</th>
<th>$rT_3$ (mean ± s.d.)</th>
<th>$[^{13}C_9]T_4$ (mean ± s.d.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0·1</td>
<td>103·0 ± 4·0 (4·3)</td>
<td>95·0 ± 4·0 (4·2)</td>
<td>96·0 ± 2·0 (2·1)</td>
<td>101·0 ± 6·0 (5·9)</td>
</tr>
<tr>
<td>0·2</td>
<td>105·5 ± 5·5 (5·2)</td>
<td>94·0 ± 5·5 (5·9)</td>
<td>93·0 ± 4·5 (4·8)</td>
<td>104·0 ± 4·5 (4·3)</td>
</tr>
<tr>
<td>4</td>
<td>104·4 ± 2·0 (1·9)</td>
<td>99·4 ± 2·8 (2·8)</td>
<td>98·0 ± 2·6 (2·7)</td>
<td>104·2 ± 1·9 (1·8)</td>
</tr>
<tr>
<td>80</td>
<td>97·6 ± 2·0 (2·1)</td>
<td>95·1 ± 2·1 (2·2)</td>
<td>97·6 ± 1·4 (1·4)</td>
<td>98·2 ± 1·3 (1·4)</td>
</tr>
</tbody>
</table>

$T_4$, thyroxine; $T_3$, triiodothyronine; $rT_3$, reverse-triiodothyronine.
was confirmed at the end of the experiment by macroscopic observation at necropsy. In addition, serial sections from tracheal tubes (area of thyroid glands in Tx rats) were reviewed by a pathologist and hypertrophy or hyperplasia of follicular epithelial cells were not observed.

**Experiment 1**

Ten rats were divided into two groups \((n=5)\), the Tx and control groups. Serum samples were collected for 3 weeks. In control rats, serum TSH was maintained at \(2.2\,\text{ng/ml}\) over the experimental period. All samples were obtained between 0900 and 1100 h to minimize fluctuations in thyroid hormones (Jeremiah et al. 1990).

**Experiment 2**

Five Tx rats were allowed 4 weeks to achieve steady-state plasma thyroid hormone concentrations after Tx. \([^{13}\text{C}_9]\text{T}_4\) was administered intravenously to Tx and control rats at a dose of \(1.5\,\text{mg/kg}\). Serum samples were obtained 5 min after \([^{13}\text{C}_9]\text{T}_4\) administration, then at every 24 h for 2 weeks, and every 48 h for an additional week. All samples were kept frozen at \(-20^\circ\text{C}\) until analysis.

**Online SPE LC–MS/MS**

The HPLC system (Shimadzu, Kyoto, Japan) consisted of a SCL-10Avp system controller, three LC-20AD pumps connected to an FCV-11AL reservoir selection valve, an SIL-HTc autosampler, and a CTO-20A column oven equipped with an FCV-12AH six-port switching valve for online extraction. The SPE column was a Shim pack MAYI-ODS, 2.0 mm I.D. \(\times 10\,\text{mm}\), 50 \(\mu\text{m}\) (Shimadzu) maintained at \(45^\circ\text{C}\). The analytical column was a Synergi Polar-RP 80A, 2.0 mm I.D. \(\times 50\,\text{mm}\), 4 \(\mu\text{m}\) (Phenomenex, Utrecht, The Netherlands) maintained at \(45^\circ\text{C}\). The mobile phases were 1\:vol\% formic acid (A-1), 0\:05\:vol\% acetic acid (A-2), methanol (B), and 0\:05\:vol\% acetic acid/methanol (95:5, v/v), respectively. The LC conditions are listed in Table 1. An API5000 triple-quadrupole mass spectrometer (AB SCIEX, Foster City, CA, USA) equipped with a TurboIonSpray source was operated in the positive ion multiple reaction monitoring (MRM) mode to perform the analysis. The transitions to monitor were selected for each compound: \(m/z\) 777.70 \(\rightarrow\) 631.50 for \([^{13}\text{C}_0]\text{T}_4\), \(m/z\) 651.77 \(\rightarrow\) 507.73 for \([^{13}\text{C}_0]\text{T}_3\), \(m/z\) 786.71 \(\rightarrow\) 739.90 for \([^{13}\text{C}_9]\text{T}_4\), and \(m/z\) 782.75 \(\rightarrow\) 735.90 for \([^{2\text{H}}_5]\text{T}_4\).

**Sample preparation**

A 20 \(\mu\text{l}\) aliquot of rat serum was mixed with 60 \(\mu\text{l}\) of internal standard solution (2 \(\,\text{ng/ml}\) of \([^{2}\text{H}_5]\text{T}_4\)). After vortex mixing, the mixture was centrifuged (16 000 \(g\) for 5 min at \(10^\circ\text{C}\)). Then, 40 \(\mu\text{l}\) of \(0.1\,\text{vol}\%\) formic acid was added to the mixture and vortex mixed. After centrifugation (16 000 \(g\) for 5 min at \(10^\circ\text{C}\)), 80 \(\mu\text{l}\) of the supernatant was injected into the LC–MS/MS system. Ten calibration standards ranging from

\[\text{Figure 3} \quad \text{Changes of serum thyroid hormones concentration in control and Tx rats (A) T}_4 \text{ and (B) T}_3. \quad \text{Tx}, \text{thyroidectomy; T}_4, \text{thyroxine; T}_3, \text{triiodothyronine. All data represent the mean \pm \text{S.D. of five animals. **P<0.01.}}\]

\[\text{Figure 4} \quad \text{Serum concentrations of T}_4 \text{ and [^{13}\text{C}_9]\text{T}_4} \text{ after an i.v. administration of [^{13}\text{C}_9]\text{T}_4} \text{ to control (A) and Tx (B) rats. Tx, thyroidectomy; T}_4, \text{thyroxine.}}\]
0.1 to 100 ng/ml were prepared from charcoal-stripped rat serum. Similarly, four quality control samples were prepared with concentrations of 0.1, 0.2, 4 and 80 ng/ml. These levels were chosen to demonstrate the precision and accuracy of the method at the lower limit of quantitation (LLOQ) as well as at low, medium and high concentrations on the calibration curve.

**Data analysis**

The turnover rate ($k_{el}$) was determined by plotting serum concentration of $[^{13}C_9]$T4 against time in a semilog plot,

$$C = C_0 \times e^{-k_{el} \times t},$$

where $C$, serum concentration of $[^{13}C_9]$T4 at time ($t$); $C_0$, serum concentration of $[^{13}C_9]$T4 at time zero; $t$, time (day) and $k_{el}$, turnover rate. The half-life ($t_{1/2}$) of $[^{13}C_9]$T4 was calculated as $t_{1/2} = 0.693/k_{el}$ (Kasuya et al. 2005).

The supply rate (SR) of T4 was calculated as follows:

$$SR = C_{ss} \times Vd \times k_{el},$$

where $C_{ss}$, steady state serum T4 concentration; $Vd$, volume of distribution and $k_{el}$, turnover rate. $Vd$ was calculated by the equation

$$Vd = \frac{X_0}{C_0},$$

where $X_0$, dose of $[^{13}C_9]$T4 administered and $C_0$, serum concentration of $[^{13}C_9]$T4 at time zero.

**Statistical analysis**

The data are expressed as the mean ± s.d. Statistical significance was calculated by unpaired Student’s t-test. A $P$ value <0.01 was considered significant.

**Results**

**Online SPE LC–MS/MS**

For T4, T3, rT3 and $[^{13}C_9]$T4, intra-day precision and accuracy were evaluated by analysis of the 0-1, 0-2, 4 and 80 ng/ml quality control samples. The results are summarized in Table 2. Overall, the intra-day precision was <5-9% for each analyte at each quality control level, and the accuracy was between 93-0 and 105-5%. Therefore, the LLOQ of each analyte was established at 0.1 ng/ml.

These methods represent a specific and reliable technique for measurement of endogenous and stable isotopically labeled thyroid hormones in serum with a high degree of precision and accuracy.

**Serum concentrations of endogenous thyroid hormones**

After Tx, T4 and T3 levels decreased rapidly and achieved a steady state 7 days after treatment (Fig. 3). The steady-state T4 and T3 concentrations were ~2 and 0-1 ng/ml, respectively. The rT3 concentration also rapidly decreased in Tx rats, dropping a level lower than the quantification limit (0.1 ng/ml). In control rats, T4, T3, and rT3 concentrations were maintained at ~50, 0.82, and 0.76 ng/ml, respectively, throughout the experimental period.

**Supply and turnover rates**

After a single i.v. administration of 1.5 mg/kg $[^{13}C_9]$T4 to Tx and control rats, $[^{13}C_0]$T4 level was maintained at ~2.6 and 50 ng/ml, respectively, throughout the experimental period (Fig. 4). In contrast, $[^{13}C_9]$T4 levels in both Tx and control rats rapidly decreased after administration of $[^{13}C_9]$T4, and were below the threshold for quantification by 9 days after treatment.

The turnover rate of serum $[^{13}C_9]$T4 in Tx rats was 0.60 ±0.02 day$^{-1}$, approximately twofold slower than in controls (1.19 ±0.10 day$^{-1}$), and the $t_{1/2}$ was ~1-2 days (Table 3 and Fig. 5).

![Figure 5 Turnover of serum T4 in control and Tx rats. Tx, thyroidectomy; T4, thyroxine.](image-url)
The T₄ SR was 39.9 ± 5.9 ng/day (2.3-fold of that in control rats). The T₄ elimination rate in controls (ERcnt), which was calculated using the kinetics parameters of control rats, was ~2-3-fold faster than ERtx (Fig. 6 and Table 4).

### Discussion

Concentrations of thyroid hormones in the plasma are strictly controlled by TSH, which is subject to negative feedback regulation by thyroid hormones. The major form of thyroid hormone secreted from the thyroid gland is T₄. In hypothyroidism, T₄ is orally administered to maintain plasma thyroid hormone levels at a normal level. Although thyroid hormone levels are typically utilized to diagnose thyroid disease, thyroid hormone kinetics may also provide valuable information about the causes of thyroid hormone disorders.

To investigate the turnover rate of T₄ and changes in T₄ metabolism resulting from hypothyroidism, we synthesized a stable isotope-labeled compound and established an online SPE–MS/MS method. Conventional HPLC sample preparation is still labor-intensive and time-consuming, and requires many steps. Protein precipitation (PPT) is considered to be the fastest and simplest approach for extraction of hydrophilic and hydrophobic compounds. However, the extraction ratio, reproducibility, and selectivity of PPT are not sufficient to determine the concentrations of each analyte. Thus, we developed an online SPE assay using automated sample preparation instead of additional manual sample cleanup. The Shim Pak MAYI-ODS column was chosen for this assay because it can accommodate a large injection volume of PPT sample. Chromatographic focusing in the gradient elution produced very narrow peaks despite the large injection volume of 80 µl. Completely resolved peaks were obtained for T₄, T₃, rT₃ and [¹³C₉]T₄. Thorough cleanup by online SPE with high-efficiency LC separation and specific MRM detection conferred high selectivity. We used a novel combination of stable isotope-labeled tracer and online SPE LC–MS/MS to study thyroid hormone supply and turnover rates in Tx rats. Serum thyroid hormones (T₄, T₃ and rT₃) decreased as a result of surgical Tx, but were not completely abolished. At the steady state, hormone SRs are assumed to be in equilibrium with the elimination rates. Thus, we are able to estimate the elimination rate of labeled T₄. In Tx rats, although endogenous T₄, T₃ and rT₃ maintained at a constant level throughout the experimental period, the [¹³C₉]T₄ level declined with a half-life of about 1.2 days. These findings indicate that serum T₄ in Tx rats is maintained at a constant low level due to supply of T₄ in extra-thyroidal tissues (e.g. secretion of extra-thyroidal storage, enhancement of enterohepatic recirculation and production in extra-thyroidal tissues) (SR: 39.9 ± 5.9 ng/day). A few previous reports in the literature have also suggested an unknown extrathyroidal source of thyroid hormone (Evans et al. 1966, Taurog & Evans 1967, Obregon et al. 1981). In recent years, Meischl et al. (2008) reported that cardiomyocytes can produce thyroid hormone under specific experimental conditions. More recently, expression of transporters that act through thyroid hormone secretion (Visser et al. 2008, Cosmo et al. 2010) and 1⁻⁻ intake (de Carvalho & Quick 2011) have been reported in extrathyroidal organs. However, to the best of our knowledge, these studies have never been followed up to quantitatively elucidate the extrathyroidal sources of T₄. Moreover, in Tx rats, the turnover rate of T₄ was approximately twofold slower than in controls. This suggests that disappearance of serum T₄ is suppressed by Tx, and the magnitude of the suppression was estimated to be 50-3 ng/day.

TX may upregulate deiodination from T₄ to T₃ to mitigate hypothyroidism. Conversely, T₄ glucuronidation and sulfation may be inhibited by Tx. Changes in urinary excretion of T₄ and deiodination of T₄ to rT₃ following Tx warrant further investigation. In addition to these changes in T₄ metabolism, Vranckx et al. (1994) reported that Tx induces expression of T₄-binding globulin (TBG), and suggested that regulation of TBG may thus be important for thyroid hormone homeostasis. Further study is required to completely determine the mechanisms of thyroid hormone homeostasis after Tx.

In conclusion, we have synthesized stable isotope-labeled T₄ and have established a reliable and simple online SPE LC–MS/MS method. We have also characterized thyroid hormone kinetics in Tx rats using a stable isotope tracer. In Tx rats, serum T₄ was maintained at a constant low level due to thyroid

### Table 4

**Suppression degree of elimination of serum T₄ (T₄) in Tx rats. Data are expressed as the mean values ± s.d. (n=5)**

<table>
<thead>
<tr>
<th>ER (ng/day)</th>
<th>ERcnt</th>
<th>S (ng/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER₄</td>
<td>90.2 ± 13.3</td>
<td>50.3</td>
</tr>
</tbody>
</table>

Tx, thyroidectomy; ER, elimination rate; ER, supply rate (SR) (in steady state); ERtx, SR for Tx rats. ERcet =Css×Vd×kel; where Css is 2-6 ng/ml for Tx rats, kel and Vd are each value for control rats. S, suppression degree for elimination of T₄, S = ERcet − ERtx.
hormone supply from extra-thyroidal tissues and decreased degradation of $T_4$. The powerful online SPE LC–MS/MS tool can be used to investigate thyroid hormones kinetics and metabolism, and thus has the potential to be used as a diagnostic tool and to investigate the pathogenesis of thyroid disease. Our methods can be applied to future kinetic and metabolic studies of $T_4$ in the hyperthyroid and hypothyroid states in humans.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

Funding

This research did not receive any specific grant from any funding agency in the public, commercial or not-for-profit sector.

Acknowledgements

We thank Dr Masanori Murakoshi for critically reviewing the manuscript and for histo-pathological examinations of tracheal tube.

References


Received in final form 1 April 2011

Accepted 8 April 2011

Made available online as an Accepted Preprint 8 April 2011