Thyroid hormone and the stunned myocardium

Dimitri Novitzky and David K C Cooper

Formerly Professor of Cardiothoracic Surgery, University of South Florida, Tampa, Florida, USA
1Thomas E. Starzl Transplantation Institute, University of Pittsburgh Medical Center, Starzl Biomedical Science Tower, W1543, 200 Lothrop Street, Pittsburgh, Pennsylvania 15261, USA

Abstract

Acute critically ill patients experience a rapid decline in plasma free thyroid hormone levels (free triiodothyronine (FT₃) and free levothyroxine (FT₄)) with a marked elevation of reverse T₃, recognized as the euthyroid sick syndrome (ESS) or low-T₃ syndrome. The ESS is also often associated with depressed myocardial function, sometimes referred to as the ‘stunned myocardium’. Its clinical effects may vary from minimal hemodynamic impairment to cardiogenic shock. Medical management may range from aspirin alone to placement of a left ventricular assist device. With adequate supportive therapy, recovery usually occurs within days or weeks. The effect of T₃/T₄ therapy has been studied in three conditions in which the ESS and myocardial functional depression have been documented – i) transient regional myocardial ischemia and reperfusion, ii) transient global myocardial ischemia in patients undergoing cardiac surgery on cardiopulmonary bypass, and iii) transient inadequate global myocardial perfusion in brain-dead potential organ donors. Under all three conditions, myocardial ischemia leads to rapid loss of high-energy phosphates, accumulation of myocardial tissue lactate, and probably loss of homeostasis of cytosolic calcium, which may further increase cell injury. There is an inability to generate ATP through the Krebs cycle, which reduces the high-energy phosphate pool essential for all cell ATPases. Under all three conditions, following administration of T₃/T₄, the myocardial dysfunction was rapidly reversed. We, therefore, cautiously advocate the use of thyroid hormonal therapy to any patient with the ESS and/or a stunned myocardium.

Key Words
- brain death
- cardiopulmonary bypass
- myocardium, stunned
- thyroid hormones

Introduction: thyroid hormone and the euthyroid sick syndrome

Thyroid hormone production, function, and interaction with other endocrine systems are well understood (Flood et al. 2013, Duarte-Guterman et al. 2014). Control of the thyroid gland is regulated by hypothalamic and paraventricular nuclei, which release thyroid-releasing hormone directly into the hypothalamic hypophyseal portal venous system, which drains into the anterior pituitary gland, stimulating the release of thyroid-stimulating hormone (TSH), which controls thyroid hormone storage and release (Fliers et al. 2006). Most (90%) of the secreted thyroid hormone is tetraiodothyronine (T₄, levothyroxine) and the remaining 10% is triiodothyronine (T₃). These hormones are rapidly bound to proteins, and the amount that remains free in the plasma is small; approximately 5% of T₃ (FT₃) and 10% of T₄ (FT₄) is free (Fliers et al. 2006).

T₃ is the active thyroid hormone, and all T₄ secreted by the thyroid gland is converted into T₃ or reverse T₃ (rT₃). Intracellular T₃ has approximately 20 times more potency...
Thyroid hormones are essential for proper aerobic mitochondrial function, generation of high-energy phosphates, activation of adenine nucleotide transferase, and prevention of tissue lactic acidosis (Novitzky et al. 1988a). T₃/T₄ play an important role in intracellular homeostasis of ionized calcium (Straub 2014), thereby avoiding calcium-induced injury (Oshiro et al. 2001), mobilizing cytosolic calcium into the sarcoplasmic reticulum, and participating in calcium uptake/calcium release during depolarization/repolarization of myocytes (Zarain-Herzberg & Alvarez-Fernandez 2002). They also play a role in the up-regulation of β adrenergic receptors and protein synthesis. Thyroid hormones affect excitation/contractility coupling and have inotropic properties (Ririe & et al. 2001), which are dose-dependent (Snow et al. 1992), and are strong vasodilators of systemic arteries, including coronary arteries (Klein 2001).

Acute critically ill patients (medical or surgical), who prior to developing the illness/condition were euthyroid and had normal plasma free thyroid hormone levels, experience a rapid decline in FT₃ and FT₄, with a marked elevation of plasma levels of rT₃ (Warner & Beckett 2010). FT₃ plasma levels may fall by 70–90%. The severity of reduction in FT₃/FT₄ has been shown to correlate with patient mortality. TSH levels usually remain within the normal range, though in very sick patients they may be reduced, but not as markedly as FT₃ and FT₄. These acute changes are recognized as the euthyroid sick syndrome (ESS) or low-T₃ syndrome.

Following exposure to an acute pathogenic event (medical, surgical, traumatic), ESS has been observed in the majority of patients admitted to a medical or surgical intensive care unit in practically every acute or chronic stress condition (Table 1). Its cause may be multifactorial. ESS is frequently associated with the presence of high levels of plasma and/or tissue catecholamines (endogenous or exogenous) (Mebis et al. 2009), but may also be associated with an inflammatory response. Among multiple markers, tumor necrosis factor-alpha (TNF-α) may participate in the mediation of the ESS. For example, the infusion of TNF-α in humans results in a decrease in serum T₃, T₄, and TSH levels, and a rise in rT₃ (van der Poll et al. 1990). The infusion of interleukin-1 (IL1) (Hermus et al. 1992), IL6 (Bartalena et al. 1994, Stouthard et al. 1994), or interferon-alpha (IFN-α) (Corssmit et al. 1995) produces a similar effect. As both TNF-α and IL1α can induce the release of IL6, this indicates that IL6 may be the mediator of cytokine-induced changes in thyroid hormones.

ESS is often associated with depressed myocardial function. Inadequate organ perfusion, in turn, precipitates an inflammatory response, with release of oxygen free radicals, which may further compromise myocardial contractility. Multiorgan failure is not unusual (Gou et al. 2006). The myocardial dysfunction is usually transient and is sometimes referred to as the ‘stunned myocardium’.

The stunned myocardium and the ESS

The term ‘stunned myocardium’ is used in conditions in which the myocardium is depressed following a regional or global ischemic event (Bolling et al. 1994, Kloner & Jennings 2001, Luo et al. 2010, Heusch 2013). The affected myocardial territory may range from a small volume of myocardial tissue to the entire heart. Its clinical effects may, therefore, vary from minimal hemodynamic impairment to cardiogenic shock. Transient ischemic events may not be severe enough to induce myocyte necrosis, but the myocardium loses its ability to perform work normally. The level of the functional depression is related to the extent of the myocardial ischemia. Its natural course is for recovery to occur within days or possibly weeks. Medical management may range from the administration of aspirin alone to placement of a left ventricular assist device.

Thyroid hormones in the treatment of the ESS

Plasma thyroid hormone values recover once the underlying pathological condition, e.g., pneumonia, myocardial ischemia related to open heart surgery, has been

Table 1  Conditions in which the euthyroid sick syndrome (ESS) has been described

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute myocardial infarction, post-cardiac arrest, and low</td>
<td>cardiac output related to myocardial dysfunction</td>
</tr>
<tr>
<td>Autoimmune diseases</td>
<td></td>
</tr>
<tr>
<td>Brain injury and brain death, including brain-dead organ donors</td>
<td></td>
</tr>
<tr>
<td>Cardiac surgery on cardiopulmonary bypass</td>
<td></td>
</tr>
<tr>
<td>Chronic infection (e.g., cystic fibrosis, tuberculosis, fungal)</td>
<td></td>
</tr>
<tr>
<td>Critically-ill ICU patients (from any cause)</td>
<td></td>
</tr>
<tr>
<td>Diabetes (uncontrolled, ketoacidosis)</td>
<td></td>
</tr>
<tr>
<td>End-stage organ failure, including patients awaiting organ transplantation</td>
<td></td>
</tr>
<tr>
<td>Fasting (severe prolonged)</td>
<td></td>
</tr>
<tr>
<td>Malignant disease</td>
<td></td>
</tr>
<tr>
<td>Sepsis</td>
<td></td>
</tr>
<tr>
<td>Shock (hemorrhagic, septic)</td>
<td></td>
</tr>
<tr>
<td>Steroid therapy (prolonged)</td>
<td></td>
</tr>
<tr>
<td>Trauma</td>
<td></td>
</tr>
</tbody>
</table>

*From Novitzky D & Cooper DKC 2013 Thyroid hormone therapy to the recipient of a heart from a brain-dead donor. In The Brain-Dead Organ Donor: Pathophysiology and Management, p 322. Eds D Novitzky & DKC Cooper. New York: Springer (with permission).
reversed. The current consensus, therefore, is that patients exhibiting the ESS should not be subjected to thyroid replacement therapy as it is not believed that the administration of thyroid hormone changes the outcome of the primary disease (Bello et al. 2010, Pappa et al. 2011).

In our experience, however, the administration of T₃/T₄ has been rewarding in conditions in which myocardial ‘stunning’ plays a role. These include any condition in which a period of regional or global myocardial ischemia (inadequate blood perfusion) has occurred followed by revascularization and/or reperfusion. In particular, the effect of T₃/T₄ therapy has been studied under three conditions in which the ESS and myocardial functional depression have been documented – i) transient regional myocardial ischemia and reperfusion (Heusch 2013), ii) transient global myocardial ischemia in patients undergoing cardiac surgery on cardiopulmonary bypass (CPB) (Siribaddana 2012), and iii) transient inadequate global myocardial perfusion in brain-dead potential organ donors (Novitzky et al. 1984). Under all three conditions, following administration of T₃/T₄, the myocardial dysfunction was rapidly reversed.

We, therefore, suggest that T₃/T₄ therapy may be beneficial not only for these conditions but for any condition that has resulted in a stunned myocardium.

Studies on T₃ therapy in transient regional myocardial ischemia and reperfusion in dogs

Two groups of dogs were subjected to a 15-min period of regional myocardial ischemia by snaring the left anterior descending coronary artery distal to its first diagonal branch (Novitzky et al. 1991, Yokoyama et al. 1992). After the release of the snare, the dogs were given either placebo or T₃ (0.2 μg/kg) at 30-min intervals.

Plasma FT₃ levels fell significantly during the ischemic period in both groups and continued to fall after reperfusion in the untreated group. In both groups, cardiac function deteriorated significantly during the period of ischemia, but rapidly returned to control levels after reperfusion. After 90 min of reperfusion, however, deterioration of left ventricular function was observed in untreated dogs and was significantly worse than in the T₃-treated dogs, in which hemodynamic function was maintained and, in fact, improved to levels superior to those of controls.

This study indicated that regional myocardial ischemia alone reduces FT₃ levels, and that T₃ therapy might be worthy of a trial in patients with a stunned myocardium in whom reperfusion of the myocardium takes place after variable periods of ischemia.

Studies on T₃ therapy following transient global myocardial ischemia and CPB

A significant reduction in plasma FT₃ has been documented in patients undergoing open heart procedures on CPB (Bremner et al. 1978, Robuschi et al. 1986, Novitzky et al. 1989a, Novitzky & Cooper 1990). We proposed the hypothesis that it was this reduction in circulating FT₃ that was in part responsible for a deterioration of myocardial function in such patients.

Studies in pigs and baboons

Twenty-two pigs underwent 2 or 3 h of myocardial ischemia (cross-clamping of the ascending aorta) during CPB at 26°C (Novitzky et al. 1988b). The myocardium was protected by a cardioplegic solution and by the local application of cold saline solution. After the pig was rewarmed to 37°C, CPB was discontinued, and measurements of hemodynamic function were made 10 and 70 min later. Half of the pigs received 6 μg of T₃ i.v. immediately after the removal of the aortic cross-clamp, the remainder receiving no T₃.

After 2 h of ischemia, untreated pigs showed significantly reduced myocardial function 10 min after discontinuation of CPB. By 70 min, two of five untreated pigs had died of low cardiac output, but all five T₃-treated pigs survived. After 3 h of ischemia, both groups showed some reduced function at 10 min, although the reduction was more marked in untreated animals. By 70 min, four of six untreated pigs had died of myocardial failure and all T₃-treated pigs remained alive. Surviving pigs in both groups still demonstrated some reduced function compared with values obtained before CPB.

To clarify the effect of T₃ on myocardial high-energy phosphate stores and lactate, a series of experiments were carried out in baboons undergoing 3 h of myocardial ischemia while supported by CPB (Novitzky et al. 1988c). At the end of the ischemic period, six received 6 μg of T₃, and seven received no T₃. Seventy minutes after CPB, the myocardial ATP level was significantly higher in the treated animals. In untreated animals, a steady increase in myocardial lactate occurred, and 70 min after CPB was discontinued, there was a significant difference in lactate levels between the two groups.

On the basis of these results, it was postulated that a combination of global ischemia and depletion of FT₃ resulted in reduced mitochondrial function, inhibition of the tricarboxylic acid cycle, inability to utilize oxygen aerobically with resulting increased anaerobic metabolism,
and depletion of myocardial phosphates. T₃ replacement therapy was presumed to improve mitochondrial function and increase aerobic metabolism, which led to a measured increase in myocardial phosphates.

Studies in patients undergoing open heart surgery on CPB

Initially, we administered T₃ (4–10 µg i.v.) to ten patients, either when difficulty was being experienced in weaning from CPB support (n=5) or when myocardial function remained extremely poor, despite inotropic and intra-aortic balloon pump support (n=5) (Novitzky et al. 1989b).

Within 1 h of T₃ administration, the mean plasma free T₃ level had risen from 1.03 to 3.56 µg/ml, and CPB was able to be discontinued in all cases. At 1 h, the mean arterial pressure had risen from 42 to 78 mmHg, and heart rate from 90 to 104 beats/min. The left atrial pressure had fallen from 30 to 14 mmHg, and the central venous pressure from 20 to 11 cm H₂O. All changes were statistically significant. Inotropic support had been significantly reduced or discontinued. Within 3 h, intra-aortic balloon pump support (n=2) was no longer essential.

To the best of our knowledge, T₃ had not been administered previously as an inotropic agent to patients who had undergone cardiac surgery. Although this small trial was not randomized, the results indicated that T₃ could play an important role in the rescue of failing hearts following a period of myocardial ischemia in patients who had undergone open heart surgery.

Subsequently, in two small randomized trials in patients undergoing myocardial revascularization on CPB, postoperative T₃ therapy was associated with a reduced need for inotropic support and diuretic therapy (in the first study) and improved cardiac output (in the second study) (Novitzky et al. 1989b). A later study added support to these observations (Novitzky et al. 1996).

Others subsequently continued to study the effects of CPB on thyroid hormones and the effect of thyroid hormones on myocardial function (Dyke et al. 1991, Clark 1993, Lowenstein 1993).

Studies on T₃ therapy after brain death

Myocardial stunning has been observed during and following the induction of brain death. This injury occurs at a time of massive release of endogenous catecholamines (Novitzky et al. 1984, Shivalkar et al. 1993). Electrocardiographic changes correlate well with acute ongoing myocardial ischemia and on occasions mimic an acute myocardial infarction. The catecholamine storm is short-lived, but myocardial injury can be observed under the microscope, and can be prevented by pretreatment with β blockade or calcium antagonists (Novitzky et al. 1987a).

The surge in catecholamines is associated with rapid declines in plasma levels of T₃, T₄, cortisol, insulin, and antidiuretic hormone (Novitzky et al. 1984, 1987a, Cooper et al. 1989). However, TSH remains within the normal range.

Studies in brain-dead pigs and baboons

The most relevant experiments demonstrated that brain-dead animals were unable to aerobically metabolize radiolabeled metabolites (¹⁴C-U-glucose, ¹⁴C-1-palmitate, and ¹³C-1-pyruvate) administered intravenously (Novitzky et al. 1988b). There was a major change in metabolic oxidative processes. The rate of glucose, pyruvate, and palmitate utilization was markedly reduced, and there was an accumulation of lactate and free fatty acids in the plasma, indicating a change from aerobic to anaerobic metabolism. These metabolic changes were associated with a significant decline in myocardial function. The administration of T₃ to the brain-dead animals resulted in a dramatic increase in the rate of metabolite utilization, and a reduction in the plasma concentrations of plasma lactate and free fatty acids, indicating reversal from anaerobic to aerobic tissue metabolism.

The inability of the brain-dead animal to metabolize cellular fuels aerobically indicates that the mitochondria are no longer functioning and are unable to generate high-energy phosphates; pyruvate does not enter into the mitochondria, but accumulates as lactate (Novitzky et al. 1988b, Stacpoole 1997). As time post-brain-death progresses, the inhibition of the Krebs cycle becomes greater, and mitochondrial failure leads to i) depletion of high-energy phosphates, ii) tissue lactic acidosis (Sztark et al. 2000), iii) loss of cellular homeostasis, iv) inability to maintain ionic ATPase function v) inability to maintain ion compartmentalization, and vi) deactivation of sodium/potassium cellular pumps. Increments of cytosolic calcium uptake no longer occur, and calcium is released from the sarcoplasmic reticulum into the cytosol, eventually resulting in cell death.

These results indicated that T₃ should be administered to all brain-dead potential organ donors to correct and maintain a more physiological metabolic status and thus improve organ function.

Studies in human brain-dead potential organ donors

Following brain death, recovery of myocardial perfusion results in a degree of recovery, and the heart may continue...
beating well, while it remains in the vasodilated donor (where peripheral vascular resistance is low). The further period of ischemia while the donor heart is transported and transplanted may lead to further stunning and poor prolonged myocardial depression.

Hormonal therapy that included T₃ was first administered to a series of brain-dead potential organ donors at Groote Schuur Hospital at the University of Cape Town in 1984 (Novitzky et al. 1986, 1987b, Cooper et al. 1989). The initial regimen involved the hourly administration of T₃ (2 μg), cortisol (100 mg), and insulin (20 units).

Twenty-six conventionally treated donors (with no hormonal replacement therapy) showed abnormal electrocardiograms (resembling myocardial ischemia), progressive hemodynamic deterioration requiring significantly increased inotropic support to maintain hemodynamic stability, and progressive lactic acidosis requiring frequent bicarbonate administration to maintain a normal acid–base balance (Novitzky et al. 1987b). Of this group, five (19%) of the donors were considered unsuitable as cardiac donors due to progressive cardiovascular deterioration or sudden ventricular fibrillation. Hormonal replacement therapy was administered to 21 donors, resulting in normalization of the electrocardiographic abnormalities, significant improvement in hemodynamic status, reduced inotropic support, and reduced requirement for bicarbonate. In these donors, all organs were acceptable for transplantation, which was followed by excellent organ function in the recipients.

Thyroid hormone therapy of the brain-dead potential organ donors remained controversial for many years and is still not universally administered (Macdonald et al. 2012, Rech et al. 2013). We have, therefore, recently reviewed data provided by the United Network for Organ Sharing (UNOS) on hormonal resuscitation therapy in the management of 63 593 brain-dead potential organ donors in the USA in the 10-year period 2000–2009 (Novitzky et al. 2014). There was a clear benefit in terms of the number of organs that could be procured (and transplanted) from donors that received T₃/T₄ when compared with those that did not, representing an increase in organs procured of 12.8% (P < 0.0001).

In a cohort of 40 124 donors in which details of all hormonal therapy were available, there was a clearly increased procurement/transplantation rate for the heart, lung, kidney, pancreas, and intestine when T₃/T₄ had been administered. There was no overall benefit of T₃/T₄ on liver procurement, although one subgroup showed a significantly higher procurement rate when T₃/T₄ was administered, and in the other subgroups there was no detrimental effect.

**Thyroid hormone therapy: potential mechanisms**

All of the conditions described above demonstrate variable degrees of myocardial stunning. The myocardial ischemia leads to rapid loss of high-energy phosphates, accumulation of myocardial tissue lactate, and probably loss of homeostasis of cytosolic calcium, which may further increase cell injury. There may also be mitochondrial injury, which varies in degree. There is an inability to generate ATP through the Krebs cycle, which reduces the high-energy phosphate pool essential for all cell ATPases.

Total nucleotides may remain reduced for several days, as there is a relatively slow process of de novo synthesis. The mechanism of action of the thyroid hormones has been discussed previously (Song et al. 2007, Shapiro & Baron 2013) and will not be considered in detail here. In summary, these hormones appear essential for reactivation of mitochondrial energy metabolism (in the Krebs cycle), and this contributes to hemodynamic stability. T₃ may facilitate recovery of the stunned myocardium by increasing ATP, and by activating the adenyl nucleotide transferase, enhancing the transfer of ATP from the mitochondria into the cytosol. Exogenous T₃ may have an effect on the cytosolic ATPases, affecting ATP-dependent ionic pumps, such as the calcium pumps, and calcium is rapidly mobilized in the sarcoplasmic reticulum.

For example, brain-dead organ donors suffer from various degrees of deprivation of high-energy phosphates and, as time passes, there is a progressive accumulation of tissue and plasma lactate, which, despite bicarbonate replacement, leads to progressive acidosis. These donors progressively become refractory to exogenous catecholamines and are eventually lost from the donor pool due to hemodynamic instability. The pathophysiology of brain death and the mechanisms by which hormonal therapy may improve donor organ function have recently been comprehensively reviewed (Novitzky & Cooper 2013).

The mechanisms related to the beneficial effects of thyroid hormone on the stunned myocardium have been investigated by several groups, but particularly by Pantos & Mourouzis (2014). Once thought to be detrimental to the ischemic myocardium, thyroid hormones are now recognized to have anti-ischemic and inotropic actions. Indeed, they can protect against the detrimental effects of inotropic agents that exacerbate post-ischemic myocardial dysfunction (Pantos et al. 2003a). However, in addition to their action on metabolism and calcium handling, there is increasing evidence of their effect on stress-induced intracellular signaling, in part related to inhibition of apoptosis,
mediated through thyroid hormone receptor α1 (Pantos et al. 2009, 2011, Pantos & Mourouzis 2014). This may explain why T3 is more effective than T4 (Pantos et al. 2009, 2011, Pantos & Mourouzis 2014). Thyroid hormone enhances the activation of Akt signaling, which is essential for mitochondrial function (Mourouzis et al. 2012, Adamopoulos et al. 2013). Furthermore, thyroid hormone increases basal expression and phosphorylation of heat shock protein-27, conferring protection of the myocardiurm against ischemia–reperfusion injury (Pantos et al. 2003b).

We, therefore, cautiously advocate the use of thyroid hormonal therapy to any patient with the ESS and/or a stunned myocardium, as also recommended by others (de Groot 2006). In the field of organ transplantation, T3/T4 therapy is advocated for the donor and, because the patient undergoing heart transplantation has been supported by a period of CPB (resulting in a low FT3), we also recommend T3 therapy for the recipient (Novitzky et al. 1988d, 1990). By correcting the metabolic derangements that take place in the donor, the heart will be excised with close to normal levels of energy stores that can be utilized during the period of myocardial ischemia, while the heart is transported to the recipient center and transplanted into the recipient. T3 replacement therapy administered to the recipient, before the removal of the aortic cross-clamp, will lead to rapid restoration of energy stores that may have decreased during CPB, with associated improvement in myocardial function.

In summary, patients who exhibit the ESS (whatever the underlying cause) may experience acute myocardial depression, which may require some type of cardiac support. This may involve inotropic agents, placement of an intra-aortic balloon pump, or even mechanical support of the heart. Thyroid replacement therapy may rapidly reverse this state of myocardial dysfunction, allowing all forms of myocardial support to be discontinued or significantly reduced.

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

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

Acknowledgements
The authors acknowledge with gratitude the data provided by UNOS.

References
Cooper DR, Novitzky D & Wicomb WN 1989 The pathophysiological effects of brain death on potential donor organs, with particular reference to the heart. Annals of the Royal College of Surgeons of England 71 261–266.
de Groot LJ 2006 Non-thyroidal illness syndrome is a manifestation of hypothalamic–pituitary dysfunction, and in view of current evidence, should be treated with appropriate replacement therapies. Critical Care Clinics 22 57–86. (doi:10.1016/j.ccc.2005.10.001)


Received in final form 11 August 2014
Accepted 15 August 2014
Accepted Preprint published online 15 August 2014