Compensatory hyperhidrosis following thoracic sympathectomy: a biophysical rationale

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Cramer MN, Jay O. Compensatory hyperhidrosis following thoracic sympathectomy (ETS), which involves electrocautery or clipping of the sympathetic chain to interrupt downstream innervation of sweat glands within the hyperhidrotic skin areas (7). While success rates are high (12), the most common and severe side effect of ETS is compensatory hyperhidrosis (CH), which is excessive sweat production from skin areas with preserved sudomotor function (28), such as the abdominal, lumbar, groin, thigh, and popliteal regions (4). The incidence of CH is 0% to 60% following electrocautery (2, 26) and 0% to 89% following clamping (21, 22). Severe CH, characterized by large amounts of sweat production triggered by ambient temperature, psychological stress, and exercise (7), has been reported to be as high as 28% (1, 31).

The etiology of CH is currently unknown, but potentially involves a combination of physical, physiological, and psychological factors. Chou et al. (11) proposed that CH represents a post-ETS reflex response within the hypothalamic sweat center, altered primarily by psychological (i.e., anxiety or stress) factors, and is therefore not compensatory in nature. Physiological mechanisms contributing to CH may also include a local adaptation of the sweat gland itself and/or an increased thermosensitivity of the thermal controller arising from repeated postoperative sweat gland activity. However, the presence and severity of CH following ETS may be primarily explained from a biophysical perspective by considering the reduced effective body surface area for evaporative heat loss and the greater local sweat rate needed to attain heat balance in skin areas with intact sudomotor function with various combinations of clothing, activity, and climate.

Human Heat Balance

The effective goal of the human thermoregulatory system is to maintain a steady-state core temperature by keeping the rate of heat storage (\( \dot{\sum} \)) at zero and therefore maintain a balance between the rates of metabolic heat production and net heat dissipation (in watts [W]) as described by the conceptual heat balance equation (15)

\[
\dot{S} = (M - \dot{W}) + \dot{K} + \dot{C} + \dot{R} + \dot{\dot{C}}_{\text{res}} - \dot{\dot{E}}_{\text{res}} - \dot{E}_{\text{sk}} \quad \text{[1]}
\]

where metabolic heat production (\( M - \dot{W} \)) is the difference between the rates of metabolic energy expenditure (M) and external work (\( \dot{W} \)). Dry heat exchange is the sum of conductive (\( \dot{K} \)), convective (\( \dot{C} \)), and radiative (\( \dot{R} \)) rates of heat loss. The rate of total respiratory heat loss is determined by ventilatory heat exchange via convection (\( \dot{C}_{\text{res}} \)) and evaporation (\( \dot{E}_{\text{res}} \)). Evaporative heat loss from the skin (\( \dot{E}_{\text{sk}} \)) occurs via the vaporization of sweat.

A modest thermal gradient between skin and ambient air is typically maintained through increases in skin blood flow and subsequent elevations in skin temperature during exercise and/or heat exposure. However, as ambient air temperature increases, dry heat loss is reduced due to a progressive decline of the skin-to-air temperature gradient, and the body primarily relies on the evaporation of sweat to dissipate heat. Likewise, during exercise, elevated rates of metabolic heat production must also be compensated by increased heat loss via evaporation. The rate of evaporative heat loss required to attain heat balance (\( \dot{E}_{\text{req}} \)) may be defined by rephrasing the conceptual heat balance equation (25)

\[
\dot{E}_{\text{req}} = (M - \dot{W}) + \dot{K} + \dot{C} + \dot{R} + \dot{\dot{C}}_{\text{res}} - \dot{\dot{E}}_{\text{res}} \quad \text{[2]}
\]

At a given skin temperature, this rate of heat loss may not exceed the maximum capacity for evaporative heat loss to the environment (\( E_{\text{max}} \)), defined as (25)
where $\omega$ is skin wettedness, which is the fraction of the body surface covered in sweat (considered to be 1.00 during maximal sweating) (14); $(P_{sk} - P_a)$ is the vapor pressure difference between saturated skin $(P_{sk})$ and air $(P_a)$; $R_{excl}$ is the evaporative resistance of clothing; $h_e$ is the evaporative heat transfer coefficient; and $f_{cl}$ is the ratio of clothed to nude body surface area. Values for $E_{\text{max}}$ are expressed in Watts per m² of effective BSA with sudomotor function.

While sweating responses are primarily initiated and mediated by changes in core and skin temperatures (33) and to a lesser extent nonthermal factors (18, 29), the rate of whole body sweat production at steady state is ultimately determined by $E_{\text{req}}$ (23), since once heat balance is attained, further increases in core temperature and therefore hypothalamic load error no longer occur (3, 25, 27). If $E_{\text{req}}$ exceeds $\approx 50\%$ of $E_{\text{max}}$, sweating efficiency $(S_{eff})$, which is the amount of evaporated sweat relative to the amount of sweat produced, declines rapidly (17), meaning that a greater amount of sweat production is required for a given $E_{\text{req}}$. Values for $E_{\text{max}}$ are correlated positively with the surface area available for evaporation as determined by the area of skin with innervated sweat glands, which in healthy individuals is equal to total body surface area (BSA). The ratio of $E_{\text{req}}$ to $E_{\text{max}}$ represents the effective skin wettedness required for heat balance $(\omega_{\text{req}})$, or the proportion of BSA that must be covered in sweat to provide the required rate of evaporation.

Heat Balance and Sympathectomy

By disrupting part of the sympathetic chain, ETS reduces the number of functional sweat glands not only in the targeted area but also in surrounding skin areas within the same dermatome, thus altering the pattern of sweat distribution (30) leading to varying degrees of anhidrosis in denervated skin areas (28). As depicted in Fig. 1, the head, upper arms, and torso above the nipple line become anhidrotic with a more extensive ETS (16, 28), e.g., T2–T4, leading to a $\approx 30\%$ reduction in the effective BSA (32), which is actually closer to a $\approx 40\%$ reduction when accounting for regional variations in sweat gland density that tend to be greater on the head and upper back (19, 28). When a combination of activity and climate yields an $E_{\text{req}}$ greater than zero (i.e., some evaporation is needed for heat balance), reducing the effective BSA by $\approx 30\%$ (i.e., from 2.0 m² to 1.4 m²) would demand a greater rate of local sweating per unit surface area from skin areas with preserved sweating function to produce a given absolute amount of evaporation. For example, activity that generates 350 W of metabolic heat production in an environment that presents a near-zero skin-to-air temperature gradient (e.g., 35°C) would, assuming 100% evaporation and a latent heat of vaporization of sweat of 2,426 J/g, require a whole body sweat production of $8.6 \text{ g/min}$ to attain heat balance. With a pre-ETS effective BSA of 2.0 m², average local sweat rate per unit surface area would be 0.43 mg·cm⁻²·min⁻¹; however, with a post-ETS effective BSA of 1.4 m², average local sweat rate increases to 0.62 mg·cm⁻²·min⁻¹. Because $E_{\text{max}}$ would also be reduced with a decreased effective BSA post-ETS, reductions in $S_{eff}$ would likely exacerbate the divergence between pre- and post-ETS average local sweat rates.

While the biophysical mechanisms of heat exchange have been well characterized in healthy individuals (15), alterations to heat balance following ETS have not been quantified. Using a conceptual heat balance approach, we have created a hypothetical model of the average local sweat rate (on skin areas with preserved sudomotor function) required to maintain heat balance pre- and post-ETS over a range of ambient temperatures (at a fixed relative humidity of 30%) with different combinations of activity and clothing insulation. Figure 2, top, demonstrates that following a 30% reduction in effective BSA with ETS, an augmented average local sweat rate is required under equivalent conditions with the divergence between pre- and post-ETS average sweat rates exacerbated with increasing ambient temperature due to a lower $S_{eff}$ accompanying the greater local skin wettedness following ETS. Relative to pre-ETS, the same average local sweat rate is only achieved post-ETS at a lower ambient temperature both during rest and exercise while wearing a variety of clothing ensembles. Our model also shows that, even at rest, individuals living in warm/hot climates will inevitably require CH following ETS to attain heat balance. Clinical observations apparently supporting our model include the observation that CH presents more frequently and severely during exercise (6, 13), as well as in hot/humid climates (10, 20). Moreover, resting local sweat rates at an ambient temperature of 41°C were proportionally greater in the thigh and lumbar regions relative to the reductions in forehead and upper chest sweat rate following T2–T3 ETS compared with a control group (30). These findings indicate that CH is a necessary thermoregulatory response post-ETS, since local sweat rates maintained at pre-ETS levels across the reduced effective surface area would result in a lower total evaporative heat loss and would lead to sustained

\[
E_{\text{max}} = \frac{\omega(P_{sk} - P_a)}{R_{excl}} f_{cl} \left[\frac{W}{m^2}\right]
\]

Fig. 1. Regions of body surface area anhidrosis post-endoscopic thoracic sympathectomy (post-ETS). Following extensive ETS (i.e., T2–T4), collateral denervation of sweat glands across the head, neck, upper chest, and arms can occur (grey), resulting in surface area anhidrosis of $\approx 30\%$ of body surface area (BSA). However, when accounting for regional differences in sweat gland density, surface area anhidrosis is closer to $40\%$. The area of intact sudomotor function (white) is considerably reduced post-ETS.
increases in body heat storage and core temperature. However, even with maximal CH, our model demonstrates that post-ETS patients remain at a greater risk of hyperthermia. Figure 2 also presents the effect of ETS on the heat strain index (HSI) (5) over a range of ambient temperature (Fig. 2, middle) and relative humidity (Fig. 2, bottom) values. The HSI expresses $E_{\text{req}}$ as a percentage of $E_{\text{max}}$. In physiologically compensable environments (i.e., $E_{\text{req}} \leq E_{\text{max}}$), human/environmental heat exchange is sufficient to achieve heat balance and, consequently, a steady-state core temperature. In uncompensable environments (i.e., $E_{\text{req}} > E_{\text{max}}$), a persistent heat imbalance and a progressive increase in core temperature will occur. Following ETS, the same HSI is achieved at a lower ($\approx 4$–$6^{\circ}\text{C}$) ambient temperature and relative humidity ($\approx 50$–$60\%$) due to a reduction in $E_{\text{max}}$ by virtue of a decreased effective surface area available for evaporation. Our model shows that ETS patients with CH would 1) require additional fluid intake to offset the exacerbated sweat loss associated with a reduced sweating efficiency and mitigate any dehydration-related increases in the risk of heat-related illnesses when operating in warmer environments, and 2) need to limit exposure time, use supplementary cooling methods, such as fans or air conditioning, and/or select clothing that improves evaporation (i.e., low Re,cl) to minimize the risk of heat injury and maintain work performance.

Limitations of our model include the assumption that air movement promoting dry and evaporative heat losses is uniform across the body, whereas convective flow is likely much lower across clothed skin areas. However, since clothing primarily covers skin areas with preserved sweating function post-ETS [other than the nuclear, biological, and chemical protection clothing system that covers the entire body (Fig. 2)], our model would overestimate sweating efficiency in the post-ETS condition and therefore underestimate the divergence between pre- and post-ETS average local sweat rates.
The proposed mechanism by which CH occurs is as follows: post-ETS, a reduction in sympathetically innervated sweat glands impairs evaporative heat loss, resulting in a greater elevation in core and intermediate tissue temperatures for a given \( E_{\text{req}} \) (i.e., exercise intensity and climate). This greater hypothalamic load error initiates an enhanced sweating response, augmenting sweat output from glands with uninterrupted sympathetic innervations, thereby achieving the required amount of evaporation for heat balance. Under conditions with high evaporative requirements, greater degradations in sweating efficiency due to a diminished \( E_{\text{max}} \) from surface area anhidrosis result in an increased dripping of sweat, further core temperature increases, and even greater elevations in local sweat rate with preserved sudomotor function. Finally, CH may be exacerbated by repeated sweat gland activity akin to the effects of heat acclimation (8) and may be further augmented by psychological stimuli (e.g., anxiety).

To our knowledge, only one study has reported any core temperature data in ETS patients relative to a control group (30). While differences in core temperature were not observed between groups despite evidence of CH in ETS patients, there were clear limitations with the thermometric method employed. Core temperature was measured with an in-glass oral thermometer placed under the tongue, and the lack of sensitivity of this measure to changes in thermal state are evidenced by the fact that the core temperature reported after 50 min of passive exposure to a 41°C environment, which is likely beyond the limits of thermoregulatory compensability, was the same as after 50 min in a 22°C environment. The paucity of simultaneous core and skin temperatures with local and whole body sweat rate measurements clearly needs to be addressed in future research.

Perspectives and Significance

In the absence of psychological stimuli for sweat production, we suggest that CH is primarily a biophysically mediated thermoregulatory response that compensates for the collateral denervation of nontarget skin areas within a dermatome by augmenting sweat production from areas with intact sudomotor function. Under these conditions, a psycho-physiological adjustment is not necessarily required; the increase in sweat production associated with CH would be primarily determined by heat balance requirements.

The debilitating nature of CH demands a re-evaluation of its putative mechanisms. Understanding these mechanisms will facilitate a more accurate prediction of the incidence and severity of CH following ETS based on the degree of surface area anhidrosis and the range of climate and activity levels to which the individual is typically exposed, leading to more informed decisions by those with primary hyperhidrosis considering an ETS procedure. Future research should be directed at 1) defining the magnitude of surface area anhidrosis following ETS procedures of varying extents, 2) quantifying the associated changes and distribution in whole body and local sweating, 3) determining whether ETS results in functional adaptations to sweat glands and alterations to sudomotor thermosensitivity, and 4) dissociating psychologically-mediated sweat production following ETS from the increased local sweat rate associated with the altered local evaporative requirements for heat balance.

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AUTHOR CONTRIBUTIONS

M.N.C. and O.J. analyzed data; M.N.C. and O.J. interpreted results of experiments; M.N.C. and O.J. prepared figures; M.N.C. and O.J. drafted manuscript; M.N.C. and O.J. edited and revised manuscript; M.N.C. and O.J. approved final version of manuscript; O.J. conception and design of research.

REFERENCES


