Compensatory hyperhidrosis following thoracic sympathectomy: a biophysical rationale

Matthew N. Cramer and Ollie Jay
Thermal Ergonomics Laboratory, School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, Ottawa, Ontario, Canada

Submitted 29 July 2011; accepted in final form 22 November 2011

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 100% 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 cen-

Primary hyperhidrosis is characterized by excessive palmar, plantar, and/or axillary sweating beyond thermoregulatory requirements. Severe cases are often treated surgically by endoscopic 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 100% 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 cen-

Compensatory hyperhidrosis following thoracic sympathectomy: a biophysical rationale

Matthew N. Cramer and Ollie Jay
Thermal Ergonomics Laboratory, School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, Ottawa, Ontario, Canada

Submitted 29 July 2011; accepted in final form 22 November 2011

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 100% 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 cen-

Primary hyperhidrosis is characterized by excessive palmar, plantar, and/or axillary sweating beyond thermoregulatory requirements. Severe cases are often treated surgically by endoscopic 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 100% 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 cen-

Primary hyperhidrosis is characterized by excessive palmar, plantar, and/or axillary sweating beyond thermoregulatory requirements. Severe cases are often treated surgically by endoscopic 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 100% 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 cen-

Primary hyperhidrosis is characterized by excessive palmar, plantar, and/or axillary sweating beyond thermoregulatory requirements. Severe cases are often treated surgically by endoscopic 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 100% 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 cen-
\[ E_{\text{max}} = \frac{\omega (P_{\text{sk}} - P_{a})}{R_{\text{cl}} (h_{e} f_{c})} \quad [\text{W/m}^2] \] (3)

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); \((P_{\text{sk}} - P_{a})\) is the vapor pressure difference between saturated skin \((P_{\text{sk}})\) and air \((P_{a})\); \(R_{\text{cl}}\) is the evaporative resistance of clothing; \(h_{e}\) is the evaporative heat transfer coefficient; and \(f_{c}\) 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 \(\sim 50\%\) of \(E_{\text{max}}\), sweating efficiency \((S_{\text{eff}})\), 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 skinomere, 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 \(\sim 30\%\) reduction in the effective BSA (32), which is actually closer to a \(\sim 40\%\) 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 \(\sim 30\%\) (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 \(\sim 8.6\) 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 \(S_{\text{eff}}\) 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 \(S_{\text{eff}}\) 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
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., $E_{\text{req}}/E_{\text{max}}$) 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 ($\sim 4 – 6^\circ$C) ambient temperature and relative humidity ($\sim 50 – 60\%$) 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 $R_{\text{cl}}$) 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 sudomotor function (other than the nuclear, biological, and chemical protection clothing system that covers the entire body), 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.

Fig. 2. Average local sweat rate to achieve heat balance and the heat strain index (HSI) pre- and post-ETS. The calculated average local sweat rate to achieve heat balance from skin areas with preserved sudomotor function is shown over a range of ambient temperatures (top). The HSI, expressed as $\% E_{\text{max}}$, is shown over a range of ambient temperatures (middle) and over a range of relative humidity levels (bottom). Shaded areas indicate physiological uncompensability (i.e., $E_{\text{req}}/E_{\text{max}}$). Calculations were based on an individual with a BSA of 2.0 m$^2$, which is effectively reduced by 30% to 1.4 m$^2$ post-ETS; a relative humidity of 30% (top and middle); an ambient temperature of 25°C (bottom); two rates of metabolic heat production indicating either rest (130 W) or moderate exercise (350 W); and while wearing various clothing ensembles: rest wearing a business suit (25); exercise wearing summer athletic clothing (25); exercise wearing an American football uniform (24); and exercise wearing the Canada nuclear, biological, and chemical protective clothing system (9).
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.

**ACKNOWLEDGMENTS**

We thank Michael Kohl for providing the illustration in Fig. 1.

**GRANTS**

This work was supported by a Natural Sciences and Engineering Research Council of Canada Discovery Grant (to O. Jay).

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the author(s).

Part of this work was originally conducted by Dr. Jay for inclusion in a court case report commissioned by Jonathan Bishop, Quebec City, Canada.

**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**


AJP-Regul Integr Comp Physiol • doi:10.1152/ajpregu.00419.2011 • www.ajpregu.org


