

Energy Expenditure and Fluid and Electrolyte Requirements in Anesthetized Infants and Children

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In 31 infants and children (body weights ranging from 3.8 to 25 kg), indirect calorimetry was used for the calculation of energy needs (E, kcal/h), fluid volume (FV, ml/h) and electrolyte requirements (sodium, Na⁺, and potassium, K⁺, mmol/liter per hour) during halothane anesthesia. The children were spontaneously breathing and undergoing minor lower abdominal or orthopedic surgery. A nonbreathing anesthesia circuit was used, and gas concentrations were measured by a mass spectrometer. For the evaluation of ventilation during periods of measurements, pneumotachography and in-line capnography were used. Energy expenditure was related to weight and followed the regression equation $E = 1.5 \times \text{kg} + 5.2$; $r = 0.96$. The energy needs were converted to fluid volumes according to the water requirements for heat production, which resulted in the following relationship between FV and weight: $FV = 2.4 \times \text{kg} + 8.6$; $r = 0.96$. The energy expenditure was up to 50% lower than in previous reports. Extrapolations of energy needs from awake values are inappropriate to use during halothane anesthesia. Because of the low energy expenditure during anesthesia, requirements of sodium and potassium were up to 50% lower than those based on previous standards. (Key words: Anesthesia, pediatric; fluid balance; metabolism. Anesthetics, volatile: halothane. Measurement techniques: indirect calorimetry; mass spectrometry.)

THE METABOLIC RATE not only reflects cellular activity of the body, but also affects fluid and electrolyte balance.^{1,2} Standard metabolic rates have previously been published for awake infants and children,³⁻⁵ and estimates of the energy expenditure for hospitalized awake children⁶ have been extrapolated to the anesthetic state.⁷ Volatile anesthetic agents depress metabolic function in organs such as the brain, liver, heart, and kidneys.⁸ These organs make up at least two-thirds of the total energy delivery in adults, and an even higher portion in infants and children.⁹ Hence, it is likely that the metabolic rate is different in awake and anesthetized children, and that this difference should have an impact on fluid and electrolyte balance.

In the present study, indirect calorimetry was used for the calculation of energy requirements in children during halothane anesthesia. The aims of the study were: 1) to measure the actual energy needs during anesthesia in children, 2) to evaluate whether extrapola-

tions from awake values are appropriate for the anesthetized state, and 3) to address the question of the relationship of energy expenditure to fluid and electrolyte requirements.

Materials and Methods

This study was approved by the Institutional Review Board at the Mayo Clinic, and parental consent for the study was obtained in each case. Thirty-one ASA physical status 1 children between 20 days and 7 yr of age and with body weights ranging from 3.8 to 25 kg were investigated. All patients were fasting for at least 4-5 h before induction of anesthesia. They were scheduled for minor, general, urologic, or orthopedic pediatric surgical procedures, and had body weights within the normal range for a pediatric population.

ANESTHESIA

Premedication was not used. Anesthesia was induced with halothane in oxygen/nitrous oxide ($FI_{O_2} \approx 0.5$). The trachea was intubated without the use of muscle relaxants. For an airtight connection, cuffed tracheal tubes (Mallinckrodt) were used. The children were allowed to breathe spontaneously in a nonbreathing anesthesia circuit (Hans-Rudolph valve 2210B; dead space, 2.3 ml). A mixture of halothane (mean end-tidal halothane concentration, $0.84\% \pm 0.18\%$) in oxygen and air ($FI_{O_2} \approx 0.45$) was used. Minimal alveolar concentrations (MAC) were corrected for age according to Gregory *et al.*¹⁰ for children older than 6 months of age and to Lerman *et al.*¹¹ for those who were younger. The mean value of age-corrected MAC values before surgery was 0.78 in children weighing less than 10 kg and 0.89 in those weighing more. A heated humidifier was positioned in the inspiratory limb. From induction of anesthesia to completion of the measurements, a dextrose solution at room temperature (5 g/dl) was infused at a rate of 3.6 ml/kg per hour, which is equivalent to 3 mg of glucose per kilogram per minute, to keep glycolysis at a minimum and at the same time not to use an abundance of glucose. In children weighing less than 10 kg, limbs and head were wrapped in plastic bags. In those who weighed less than 5 kg, overhead heating lamps and increased room temperature were used in addition when needed.

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MEASURING APPARATUS

To assess whether breathing was stable during measurements of oxygen consumption (\dot{V}_{O_2}) and carbon dioxide elimination (\dot{V}_{CO_2}), pneumotachography (Fleisch no. 00 for patients less than 8 kg in body weight and no. 0 for heavier patients; connection to a Micro-switch, Honeywell® 170PC differential manometer) and in-line capnography with a pediatric cuvette (Hewlett-Packard 14360A) were used. Signals for flow, volume, and end-tidal CO_2 concentrations were recorded on a six-channel recorder (General Scanning RS6-5P). The dead space of the systems (Hans-Rudolph valve and CO_2 meter included) was 5 ml with Fleisch no. 00 and 8 ml with no. 0, with inspiratory and expiratory resistances of 18 and 14 cm H_2O /liter per second, respectively, measured at a flow rate of 6 l/min. Response times and linearity were satisfactory for the measuring ranges. Body, skin, gas, and room temperatures were measured in each case.

Over a 4-min period, exhaled gas was collected in an evacuated Douglas bag 30 min after the induction of anesthesia. Before and immediately after the sampling period, end-tidal halothane concentrations were measured by the mass spectrometer sampling from the endotracheal tube connection. During the sampling period, inspired gas concentrations (from the inspiratory limb of the circuit) were measured in duplicate by the same mass spectrometer (sampling rate, 240 ml/min; Perkin-Elmer Medical Gas Analyzer, MGA 1103). The mean mixed exhaled concentrations of oxygen ($F_{E}O_2$) and carbon dioxide ($F_{E}CO_2$) in the collected gas were then immediately measured by the same mass spectrometer. The volume of gas in the bag (gas collection \dot{V}_E) was measured with a super syringe.

CALIBRATIONS

The pneumotachographs and differential manometer for flow measurements and the integrated flow for volume measurements were calibrated with an accurate pump delivering a volume of 100 ml at flow rates of 50 and 100 ml/sec. The flow from the pump was checked against a precision rotameter and the volume with a spirometer. The reproducibility of the pump flow was within $\pm 0.25\%$; after that, repeated measurements were done. Flow and volume calibrations, done before each measurement, were performed with the same gas composition, temperature, and humidification that were used during the actual measurements.

The Hewlett-Packard® capnometer was calibrated before each measurement. Preanalyzed gas mixtures with CO_2 concentrations between 1% and 7.5% were used (gas mixtures prepared gravimetrically after actual weight and percentage were determined by gas chroma-

tography). The CO_2 meter was linear within this range (1–7.5%). An end-tidal CO_2 plateau was identified in all children both before and during surgery. The mass spectrometer was routinely calibrated daily for clinical use. Before each measurement, calibrations of the mass spectrometer were also performed with certified gases containing CO_2 1.31%, O_2 35.04%, N_2 63.65%, and CO_2 3.98%, O_2 49.99%, N_2 46.03%. The accuracy and precision of the mass spectrometer were investigated by ten repeated measurements with the same certified gas concentrations. The largest deviation between these repeated measurements was 0.015%.

CALCULATIONS

Tidal volume (V_T) was measured by integrating the gas flow signal. Minute ventilation (\dot{V}_E) was obtained by multiplying V_T with the respiratory rate (f). \dot{V}_I indicates inspired minute volume. Carbon dioxide elimination (\dot{V}_{CO_2}), oxygen consumption (\dot{V}_{O_2}), energy expenditure (E), fluid volume (FV), and sodium (Na^+) and potassium (K^+) requirements were calculated according to the following expressions:

$$\dot{V}_{CO_2} \text{ (ml/min)} = (\text{gas collection } \dot{V}_E) \times F_{E}CO_2 - \dot{V}_I \times F_{I}CO_2,$$

$$\dot{V}_{O_2} \text{ (ml/min)} = \left(\frac{F_{E}N_2}{F_{I}N_2} \times F_{I}O_2 - F_{E}O_2 \right) \times (\text{gas collection } \dot{V}_E),$$

$$E \text{ (kcal/h)} = \frac{(3.9 \times \dot{V}_{O_2} + 1.1 \times \dot{V}_{CO_2}) \times 60}{1,000},$$

$$FV \text{ (ml/h)} = \frac{E}{0.603},$$

$$Na^+ \text{ (mmol/h)} = E \times 0.03,$$

$$K^+ \text{ (mmol/h)} = E \times 0.02$$

The formula for \dot{V}_{O_2} is recommended by Aukburg *et al.*¹² particularly with $F_{I}O_2$ at or below 0.5. The ratio between $F_{E}N_2$ and $F_{I}N_2$ accounts for the uptake of oxygen as well as of anesthetic gases. Energy expenditure is calculated according to the formula presented by Weir,¹³ who used the coefficients 3.9 for \dot{V}_{O_2} and 1.1 for \dot{V}_{CO_2} to compensate for the lack of measurements of protein expenditure. \dot{V}_{O_2} and \dot{V}_{CO_2} are transformed from milliliters per minute to liters per hour by a multiplication by 60 and a division by 1,000. The expression for fluid volume calculations is based on the fact that energy expenditure is equal to heat production; 0.063 kcal is needed to evaporate 1 ml of water, an additional 0.54 kcal is required for the heat of vaporization, and, thus, 0.603 kcal is burned per milliliter of water.¹⁴ Hol-

liday and Segar⁶ recommended that the relationships between energy needs and Na⁺ and K⁺ requirements be 3 mmol of Na⁺ and 2 mmol of K⁺ per 100 kcal on the basis of the electrolyte contents in human milk and cow's milk and recommendations by Darrow and Pratt.²

PROCEDURE

The anesthetic management was standardized as much as possible. After intubation of the trachea, the circuit connections were checked for leaks up to an airway pressure of 15 cm H₂O. Immediately after intubation of the trachea, air was substituted for N₂O. No measurements were made until 30 min after induction of anesthesia. Then a 4-min collection period was started, during which inspired gas concentrations were determined in duplicate. During the collection period, gas flow, tidal volume, and end-tidal CO₂ concentrations (from the in-line CO₂ meter) were continuously registered on the recorder. Body, skin, room, and gas temperatures, and blood pressure, heart rate, and O₂ saturation were also recorded. Immediately after termination of the gas collection period, mean fractions of O₂, CO₂, and N₂ were recorded by the mass spectrometer and exhaled volumes were measured by a super syringe. After these measurements, anesthetic concentration was increased and the surgical procedure begun. The same measurements were repeated about 10 min after the start of the operation during a stable state of anesthesia and surgical intervention.

STATISTICS

Mean values and standard deviations (SD) were calculated. Linear regressions were performed, and standard error of the estimate was calculated. Comparisons were carried out with paired two-tailed *t* tests, and probability values below 0.05 were considered to indicate statistical significance.

Results

During the 4-min gas collection period, ventilation was constant. This was determined by unchanged initial end-tidal CO₂ concentrations before and after each sampling period. Before surgery, respiratory rates ranged from 30 to 66 breaths per minute, with a mean value (±SD) of 42 ± 11 breaths per minute. Respiratory rates increased during surgery (highest rate, 77 breaths per minute), whereas heart rate and systolic blood pressure remained virtually unchanged. Body temperature averaged (±SD) 36.4 ± 0.6° C (range 35.8–37.7° C) and was stable in each patient during the 15 min preceding measurements. Temperature differences between skin and room (Δ S-R, ° C) ranged between 8° C

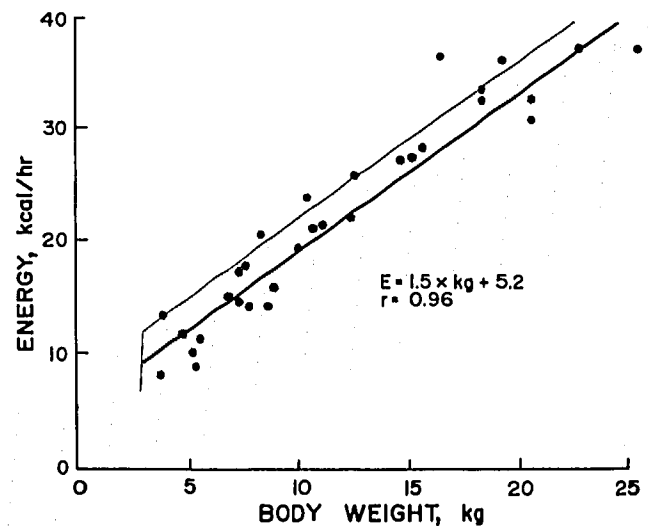


FIG. 1. Energy expenditure (E) in kilocalories per hour related to weight. Regression equation and coefficient of correlation are given, and regression line is drawn. Standard error of estimate is represented by shaded area.

and 16.5° C. In children weighing less than 10 kg, Δ S-R (mean ± SD) was 11.2° C ± 2.0° C, and for those weighing more than 10 kg, it was 12.8° C ± 1.9° C. Energy requirement correlated poorly with body temperature (*r* = 0.12) and with temperature differences between skin and room (*r* = -0.35). The mean value (±SD) of the respiratory quotient was 0.81 ± 0.15.

ENERGY EXPENDITURE

There was a linear relationship between energy needs (E, kcal/hr) and weight that, before surgery, followed the regression equation $E = 1.5 \times \text{kg} + 5.2$; *r* = 0.96 (fig. 1). Thus, a 3-kg child needed 77.6 kcal/kg per 24 h during halothane anesthesia before surgical stimulation, whereas a 25-kg child had an energy expenditure of 41.0 kcal/kg per 24 h. There were no differences between E before and during surgery; the mean values (±SD) were 22.3 ± 9.2 kcal/h and 21.7 ± 8.8 kcal/h, respectively. The coefficient of correlation for the relationship between E and weight in $\text{kg}^{3/4}$ was 0.97.

FLUID VOLUMES

The relationship between fluid volume needs (FV, ml/h) and weight was expressed by the regression equation $FV = 2.4 \times \text{kg} + 8.6$; *r* = 0.96 (fig. 2). The relatively high intercept of 8.6 made the use of mean values as ratio standards inappropriate.

ELECTROLYTE BALANCE

On the basis of the regression equation $E = 1.5 \times \text{kg} + 5.2$, sodium balance (Na⁺, mmol/h) during anesthe-

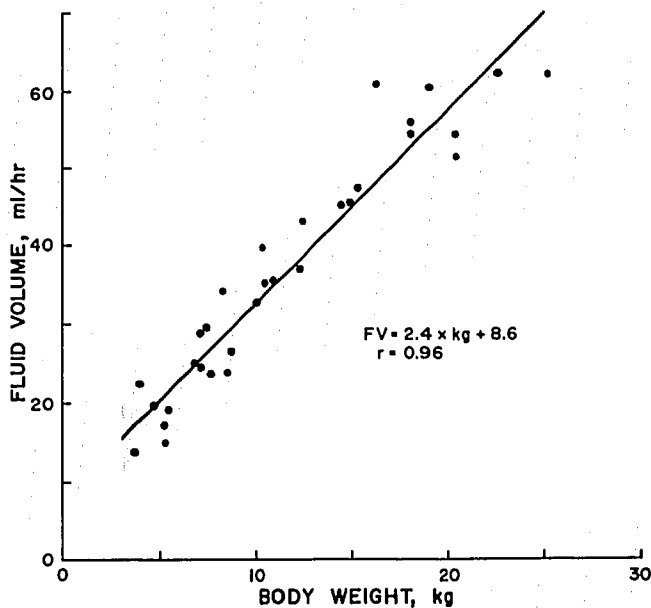


FIG. 2. Fluid volume (FV) in milliliters per hour related to weight. Regression equation and coefficient of correlation are given. Regression line is drawn. Standard error of estimate is represented by shaded area.

sia can be calculated according to the following expression: $Na^+ = 0.045 \times kg + 0.16$; similarly, the requirements for potassium (K^+ , mmol/h) can be estimated from $K^+ = 0.03 \times kg + 0.10$. These relationships are diagrammatically presented in figure 3 for hourly as well as 24-h requirements.

Discussion

This study showed that the energy expenditure during halothane anesthesia of infants and children was similar to the basal metabolic rate in the resting awake state.¹⁵ Compared to previous standards for anesthetized children,⁶ this is significantly less and will have clinical implications on the calculation of intraoperative fluid and electrolyte requirements.

The poor correlation between energy needs (E) and body temperature, as well as between E and $\Delta S-R$, was somewhat surprising, since it is known that correlation is better in the awake state.^{16,17} This finding, however, agrees with Holdcroft's¹⁸ statement that anesthetic agents reduce heat production and responses to cold environments. The most likely explanation for the poor correlation between energy needs and body temperature seems to be a combination of anesthetic effect on temperature balance, the small amount of variation in body temperature among patients, and the constant state of body temperature in each child 15 min before each measurement.

O_2 consumption and CO_2 elimination reflect carbohydrate and fat metabolism. Protein metabolism is not taken into account. Protein expenditure is best calculated from the amount of urinary nitrogen excretion for a given period. It was difficult in the present investigation to measure the amount of urine produced during the actual measurements. By the use of Weir's formula, adapted for the calculation of energy needs without measurements of urinary nitrogen,¹³ the error introduced by disregarding protein metabolism was small. Weir stated that the protein correction is similar to a decrease in energy needs of 1% when 12.5% of the total energy comes from protein expenditure. Since protein metabolism in infants is about 15% of the total,^{4,19} the error due to the lack of compensation for protein metabolism was, at the most, 1.5%.

In this study, the metabolic rate during halothane anesthesia was higher in younger than in older children, a result agreeing with values in the awake infant and child.^{3,4,20} It was somewhat surprising, however, that the metabolic rate was virtually unchanged about 10 min after the start of the operation, since most children reacted with increases in respiratory rate due to surgical stimulation. A metabolic steady state most certainly did not exist so soon after the start of surgery. The metabolic rate could have been increased in some organs and decreased in others, so that the net energy level would

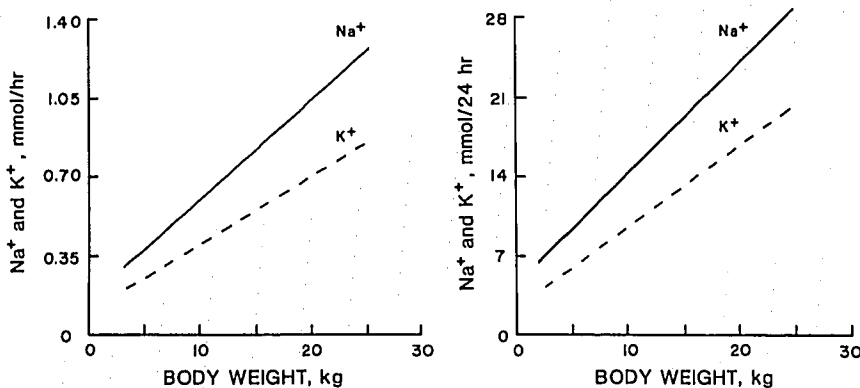


FIG. 3. Average requirement of sodium (Na^+) and potassium (K^+) hourly (left diagram) and daily (right diagram) related to weight.

be unchanged as judged from these global measurements of body metabolism.

Comparisons between energy expenditure in this study and that of Holliday and Segar⁶ in 1957 reveal a discrepancy of up to 50% (fig. 4). Holliday and Segar published their estimations of energy expenditure for awake hospitalized children. They based their values on the assumption that hospitalized children had an energy expenditure that was about midway between that during basal conditions and that during normal physical activity (fig. 4). These assumptions have been extrapolated to the anesthetic state in children.⁷ Anesthetic agents depress metabolism.⁸ Hence, energy needs are lower than those calculated with Holliday and Segar's data and are close to the awake basal metabolic state, as found by Talbot²¹ (fig. 4). Consequently, it seems inappropriate to extrapolate energy needs from assumed values in the hospitalized awake child, particularly since the energy expenditure is intimately related not only to fluid, but also to electrolyte requirements.

Despite the discrepancy in energy expenditure between this study and recommendations by Holliday and Segar, agreement between calculated fluid requirements was good. This was also true for Oh's²² modification of Holliday and Segar's data (fig. 5). The conformity in fluid requirement between the different recommendations was caused by the difference in methods for calculation. Holliday and Segar based their recommendations on estimated insensible water loss (50 ml/100 kcal/day), renal losses (66.7 ml/100 kcal/day), and oxidative water production (16.7 ml/100 kcal/day), which resulted in a requirement of 100 ml/100 kcal per 24 h. In the present study, water requirements for the production of heat were used. The conversion factor

was $\frac{1}{0.603}$, which means that 100 kcal required 166 ml

of water for its heat production.¹⁴ If Holliday and Segar's recommendations for fluid requirements of 100 ml fluid/100 kcal/day were used together with the energy expenditure in this study, intraoperative fluid volumes would be significantly reduced compared to current practice. It is, therefore, suggested that energy need (kcal/h) during anesthesia is calculated according to $1.5 \times \text{kg} + 5$ for infants and children up to 25 kg, and that the conversion factor for heat production of water

$\left(\frac{1}{0.603}\right)$ should be used for calculations of basal fluid requirements during anesthesia and minor pediatric surgery. It is emphasized that additional fluid volumes for children undergoing more extensive surgery (laparotomies [4 ml/h] and thoraco-abdominal as well as abdomino-perineal surgical procedures [6 ml/h]) are required.⁷

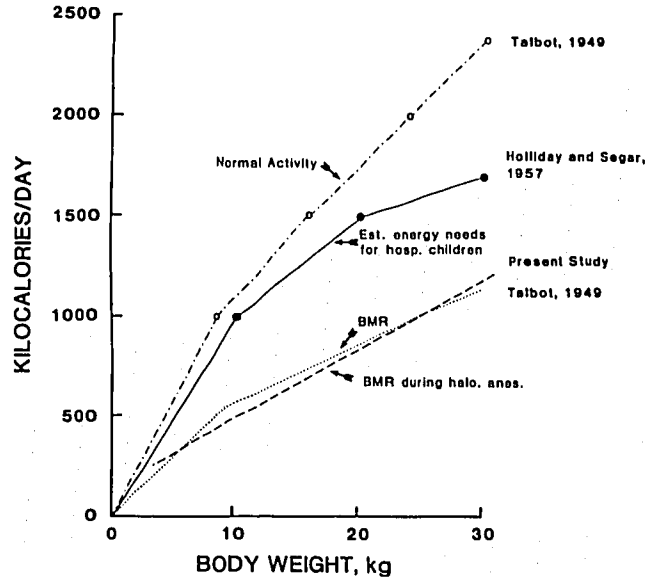


FIG. 4. Daily caloric expenditure in kilocalories related to weight both at basal metabolic rate (BMR) and at normal activity (from Talbot¹⁵). Energy needs estimated by Holliday and Segar⁶ for hospitalized children are given by continuous line, and those from present study are represented by broken line. (Modified from Holliday MA, Segar WE: The maintenance need for water in parental fluid therapy. *Pediatrics* 19:823-832, 1957. By permission of Pediatrics.)

The lower energy expenditure resulted also in a deviation between Na⁺ and K⁺ requirements in this study and those calculated from Holliday and Segar's data. In

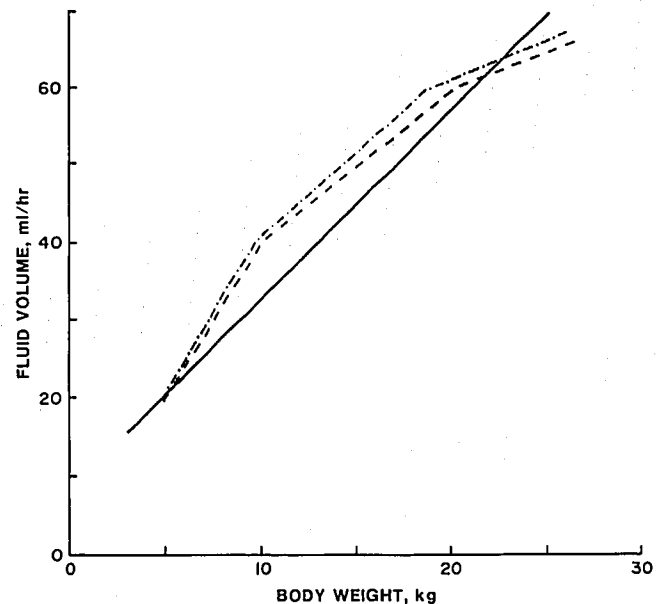


FIG. 5. Fluid volume in milliliters per hour related to weight according to three different standards. Continuous line and shaded area represent regression line and standard error of estimate found in this study. Dash-dot line denotes fluid volumes according to Holliday and Segar⁶ and dashed line those according to Oh.²²

their study, a 10-kg child had an energy expenditure of 1,000 kcal/24 h, whereas, in the present study, the same 10-kg child expended 485 kcal. The corresponding Na^+ requirements were 30 mmol/24 h according to Holliday and Segar and 15 mmol/24 h according to the present data, a deviation of 50%. The same discrepancy was also found for the calculation of K^+ requirements. Since these requirements of Na^+ and K^+ depend on the statement that 3 mmol of Na^+ and 2 mmol of K^+ are needed to burn 100 kcal, they should be challenged by direct measurements of Na^+ and K^+ balances in anesthetized children.

It is concluded that energy expenditure for clinical use during halothane anesthesia can be calculated by the expression $E \text{ (kcal/h)} = 1.5 \times \text{kg} + 5$. Extrapolations from awake values for energy expenditure are inappropriate to use during halothane anesthesia, because they doubled the actual energy needs measured in this study. Fluid volumes based on water requirements for heat production can be calculated according to the expression $FV \text{ (ml/h)} = 2.5 \times \text{kg} + 10$. Because of the low energy expenditure during anesthesia, requirements of sodium and potassium were up to 50% lower than those based on previous standards.

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