Paparella: Volume I: Basic Sciences and Related Disciplines

Section 7: General Surgical Principles

Chapter 30: Fluid and Electrolyte Balance

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Most otolaryngology patients pose no problem in maintenance of fluid and electrolyte balance. This is a mixed blessing. The rarity of a severe fluid problem simplifies the working day, but it tends to produce a complacency that leads to unquestioning, stereotyped fluid management.

Fixed-formula fluid orders result in an occasional iatrogenic misadventure that poises the unfortunate victim in an unnecessarily precarious position. If salvage is accomplished, it is time consuming and expensive in terms of hospital costs, but, most importantly, it can start a chain of complications that eventuate in death long after the patient is "in balance".

The "trick" is not to employ dazzling therapeutics in the salvage of a disaster. The ideal is to understand the underlying physiology, to recognize the patients who require more alert management, to balance the patients' fluids and electrolytes from the beginning of your care, and, finally, to learn to deal with those established fluid and electrolyte problems that may be presented. These are the broad aims of this chapter. Space does not allow an encyclopedic discussion. The references at the end of the chapter were selected for pragmatic clinical usefulness and can fill in the many vacancies.

Body Fluid Compartments and Factors Influencing Electrolyte Distribution

Body Water

Body metabolism is carried out in an aqueous medium with a dynamic steady-state balance rigidly controlling the pH and the electrolyte distribution. The amount of water in each individual varies with the fat content of his or her body.

The soft lean tissues of the body have a water content of about 73 per cent. The rest of the body consists of bone and nonaqueous fat. In looking at patients, one should develop the habit of estimating total body water at 45 to 50 per cent of body weight in the rotund fat female. Estimates should be adjusted upward in the lean young man to about 70 per cent of body weight as water. A loss of 4 liters of body water in a short, fat, 80-kg person is proportionately more serious than the same loss in an 80-kg lean, muscular individual.

The total body water is distributed into a number of compartments. The size of these compartments has been estimated by using various chemical substances with radioactive tags that are distributed in, and confined to, certain physiologic spaces. The approximate measurements are listed. When the tracer is uniformly distributed to a particular space, the volume of distribution is determined by the general formula:

Volume Distribution=[(Amount of tag given)-(quantity excreted)]/Concentration

The values given may vary, since authors differ in what is included in extracellular water. Some earlier tables include transcellular water, which embraces cerebrospinal fluid; intraocular, pleural, and peritoneal contents; the secretions of the salivary and digestive glands; and the fluid in the alimentary tract. Identification of this space is important, since equilibration rates may be slow. In certain medical and surgical conditions, there can be a massive enlargement of the transcellular space with an associated depletion of the active and circulating components of the extracellular volume.

Electrolyte Distribution

The simplest and most reasonable way to express electrolyte concentrations in body fluids and exogenously administered solutions is in terms of milliequivalents/liter (mEq/L). The relation between *milliequivalents* and *millimoles* is simple. A *mole* is the atomic weight of a substance in grams. An *equivalent* weight can be described as the atomic weight of a substance divided by its valence. A *milliequivalent* is simply 1/1000 of this amount. The conceptual convenience in relating the milliequivalent concentration of body fluid electrolytes is clear. If an ion is univalent, an equivalent is the same as mole, or 1 milliequivalent equals 1 millimole. However, if an ion is bivalent, such as calcium, 1 mole equals 2 equivalents, and 1 millimole equals 2 milliequivalents.

The solute composition of the aqueous phases of the body has been estimated in various ways. For working clinical purposes, present-day estimates *are* quite good, and the composition is shown. In the purest sense, our present views require that certain assumptions be made in tracer substance distribution, and even greater assumptions must be made when disease states are considered. It is probably fair to assume that not all intracellular fluid is the same. A condition such as potassium depletion does not affect the intracellular compartment of the liver as much as it does skeletal muscle. Since muscle is over 87 per cent of the lean parenchymal cell mass and since it is affected more in nutritional and electrolyte imbalance, it is chosen as the representative of the cellular electrolyte composition. In examining the Figure, the striking similarity of our internal aqueous environment to sea water becomes apparent. The hypertonicity (445 mEq Na^+) as well as the magnesium and sulfate levels would prevent a tolerable equilibration of the human organism to sea water.

The plasma and interstitial fluid have Na^+ as their chief anion, whereas K^+ constitutes the principal anion of the intracellular environment. How body water and solutes are distributed among the interstitial space, plasma, and cells is dependent on a series of equilibria determined by osmotic pressure, hydrostatic events, molecular diffusion, Gibbs-Donnan equilibrium, active cellular transport, and renal exchange mechanisms.

Osmolality as a Concept

If two compartments are separated by a membrane that is permeable only to water and if one compartment is then filled with water, a state of equilibrium is soon reached. At equilibrium, there is equal motion of water molecules from side to side over any one period of time. If a freely permeable solute is added to one side, it will distribute itself through both compartments in a short interval of time. As a result, the partial molal volume of water will have been decreased; hence, the activity of the water molecules will have been decreased, and fewer water molecules will move from one compartment to another in a unit of time. If a

solute that cannot traverse the membrane is added to one side, the activity of the water molecules on the left side is reduced by an amount proportionate to the molal concentration of the impermeable solute. As a result, more water molecules will move to the left than to the right. This will produce the situation as seen in the Figure. Water will enter the chamber on the left hand side of the membrane until a hydrostatic pressure is developed. The pressure increases the molecular activity of the water at the level, which forces water in the reverse direction. The pressure developed in the column of our hydrostatic model at equilibrium is a measure of osmotic pressure (the pressure of the column marked h). The difference in osmotic pressure of two solutions may be defined as the pressure that must be imposed on one solution to bring the activity of the molecules of water to the same level as in the other solution.

Osmotic forces are important in the fluid equilibria in the body. In clinical circumstances, membrane permeability varies, solute concentrations are disturbed by therapy, and active transport may be rate limited in restoring the desired balance. A practical example may be seen in a patient who is overhydrated, with renal failure and compromised cardiac reserve. When a "well-meaning" dose of mannitol is given as an osmotic diuretic, the mannitol penetrates many body compartments at a rate slower than water. In this instance, it is first seen that the slowly diffusible solute is added to the circulating plasma volume, reducing the molecular activity of plasma water. As a result, more water is added to the plasma from the extravascular space than leaves the plasma. In the intermediary state, plasma volume has expanded to a threatening degree before significant diffusion of the solute has taken place. The ultimate equilibrium is reached many hours later if the patient survives the misadventure. In planning fluid therapy, consideration must be given to the types of fluids given and the forces that distribute them in the body.

Volume Equilibrium

Osmotic activity is one of the factors participating in the distribution of water in the familiar concept outlined by Ernest Starling in 1896 to describe the forces that refill the vascular space after hemorrhage. This concept is outlined in the Figure as a refresher and should need no further review.

Ionic Equilibrium

The distribution of diffusible ions is maintained by active membrane transport of ions and passively and actively by the Gibbs-Donnan equilibrium. The Gibbs-Donnan ratio stems from a simple thermodynamic rule enunciated by J. Willard Gibbs, the great American physicist and father of chemical thermodynamic, who stated that the product of the concentration of any pair of diffusible cations and anions on one side of a membrane is equal to the product of the same pair of ions on the other side. For example:

Na^+ (plasma) x Cl^- (plasma) = Na^+ (ISF) x Cl^- (ISF).

This expression would be true if only these ions existed alone in an aqueous solution. However, as shown in Figure, plasma contains significant amounts of protein (P^-), which has negatively charged end groups. Hence, to maintain electrical neutrality, some of the sodium ions must be associated with the protein.

Hence, the osmotic concentrations are shown in the following expression:

{([Na+]Plasma + [Cl-]Plasma) / ([Na+]Excess + [P-])} = [Na+]ISF + [Cl-]ISF.

However, the product remains the same.

In the body, the osmolar concentration is slightly greater in the protein-containing side, which increases the osmotic pressure. The Gibbs-Donnan ratio is really not too great. It is 100(plasma/95(ISF) for cations and 100(plasma)/105(ISF) for anions.

Active Transport

A more powerful force in distributing ions between body spaces is active membrane transport. Active transport of Cl- and K+ have been considered. Active transport of H+ in the stomach and kidneys is well known. Nevertheless, it is the "sodium pump" that is the chief determinant of fluid space electrolyte composition. When you consider *how* ions are moved across a membrane against a concentration gradient, one is safe in saying that "the manner whereby the cellular and extracellular fluids maintain their major compositional differences is poorly understood, and is currently under investigation". No matter whether you think of sodium being excluded from cells by "little red demons" or by prostaglandin-modulated, adenylcyclase-activated, adenosine-triphosphate (ATP) - powered lipoprotein reversing layers, it must be remembered that sodium is not completely excluded from cells, and the quantity of Na+ in cells may increase with injury and disease, especially with marked nutritional wasting. Maintenance of a differential gradient requires metabolic energy.

The total exchangeable Na+ in the body is 40 mEq/kg, or about 2800 mEq in an adult. A large part of this is extracellular. With potassium, the total exchangeable K+ is about 47 mEq/kg, or about 3200 mEq. About 98 per cent of this K+ resides in the lean tissue mass, most of which is striated muscle. Since only 60 mEq of the 3200 mEq of K+ is found in the extracellular fluid, it is not surprising that serum K+ determination are a poor estimate of normalcy or depletion of total body K+.

Acid-Base Regulation

The fundamentals of the acid-base regulation in the body fluids are clearly put forth in Davenport's classic small monograph, "The ABC of Acid-Base Chemistry" (1958), and other texts. A few short paragraphs can only emphasize several clinically salient points. First, pH is a *logarithmic* expression of hydrogen ion concentration. A change of one pH unit actually represents a 10-fold change in hydrogen ion concentration. Alteration of the pH by 0.3 unit from the original pH doubles of halves the hydrogen ion concentration. Raising the pH from 7.10 to 7.40 requires that twice as many hydrogen ions be removed as when changing the pH from 7.40 to 7.70, although the pH interval is 0.3 in both instances. In Figure, the actual concentrations of H+ are given on the baseline below the pH values.

In the management of the acid end-products of metabolism, the body has only two routes of excretion, the kidneys and the lungs. Under normal conditions, carbonic acid and water are the usual end-products of caloric production. A small amount of non-volatile, complex organic acids can only be excreted via the kidney. In terms of quantity of excretion,

the lungs of an average adult excrete more than 800 mM of carbon dioxide per day. Although renal mechanisms make minor but important quantitative adjustments so that the ratio HCO_3-/H_2CO_3, which is normally 20:1, is minimally altered, HCO_3- alone or pH alone is not adequate to determine the clinical status of a patient. Two of the three factors in the Henderson-Hasselbalch equation must be known to appraise a patient's acid-base status. This is commonly done by knowing the blood pH and the pCO_2 of arterial plasma.

An alternative older method is to derive the values from accurately determined pH of the patient's blood equilibrated with two different gas mixtures with known partial pressures of CO_2 (Astrup method). The saving grace of modern clinical practice is that newer membrane techniques have made the measurement of O_2 and CO_2 content of whole blood rapid and easy to obtain. The whole blood pH is determined simultaneously. Automated devices produce a printed report in a matter of minutes.

There are three methods by which the kidneys can adjust the pH by excretion of acid residue.

Conservation of Filtered Bicarbonate. In the proximal tubule, filtered sodium is resorbed from the tubular lumen in exchange for H+, leaving H+ + HCO_3- (carbonic acid) in the tubule. Carbon dioxide is formed and diffuses back into the tubule cell, where it is available for reuse. "Bicarbonate resorption" is then a reconstitution rather than a direct resorption of molecular bicarbonate.

Phosphate Acidification. This accounts for most of the titratable acidity in the urine. The maximum pH gradient at which distal tubule cells can exchange H+ for Na+ is about pH 4.5 in the tubule. However, the presence of monohydrogen phosphate and dihydrogen phosphate (at a ratio of 5:1) allows progressive titration of the monohydrogenated to the dihydrogenated form to a ratio of 1:160 mono/di forms.

Ammonia Secretion. Ammonia (NH_3) formed from glutamine and other amino acids in the distal tubule cells diffuses freely into the tubule lumen, where a proton combines with it to produce the nondiffusible ammonium ion (NH_3 + H+ <==> NH_4+ nondiffusible). This process of ammonium production is not immediately available. It is a slow adaption of cellular enzymes that takes several days to reach a maximum. It also subsides slowly. Unfortunately this process is not available to compensate for an acute increase in acid load such as might occur from a period of anoxic arrest.

The contemporary clinician must accept the facts that the relationships of the Henderson-Hasselbalch equation are not negotiable and that blood gas determinations by membrane techniques are simple. A few evenings with the Davenport book previously referred to makes the diagnostic aspects much simpler. A modified blood gas diagram is shown in Figure. In an acute circumstance, it is possible to find a relatively pure metabolic acidosis (accumulation of excess H+), metabolic alkalosis (loss of H+), respiratory acidosis (accumulation of CO_2), or acute respiratory alkalosis (blowing-off CO_2). However, compensatory respiratory or renal mechanisms are usually stimulated or inhibited by an abnormal pH or pCO_2. As a consequence, most established abnormalities represent the sum of two vectors: (1) the disorder and (2) the shift induced by some compensatory mechanism. In Figure, the pathway to point B in a compensated metabolic acidosis is described best by

the dotted line from the area of normalcy. The disorder represents a vector from "normal" to "A" proportionate to the addition of about 25 mM of H+ per liter. If there were no respiratory compensation, the pH would be nearly 7.2, indicating a disastrous level of acidosis. The increased H+ stimulates respiration. Rapid respirations eliminate CO_2 by lowering alveolar pCO_2, which, in turn, reduces plasma carbonic acid levels and HCO_3-. This moves the patient from point A to point B on Figure. Diagnostically, the patient can be described best as having "a metabolic acidosis with a fair respiratory compensation".

Figure is the same fundamental diagram with the approximate zones for various combinations indicated. The diagrammatic, mechanistic approach is much more workable than attempting to memorize an arbitrary range of values for multiple entities. It should be emphasized that plotting a patient's movements on such a diagram can be of inestimable value in providing respiratory care on a ventilator. The changes give cogent clues to the etiology of problems and progress of therapy. It is a deliberate representation to have some of the zones in Figure overlap. This is a clinical reality in which there may be overcompensation of mechanisms: short periods of apnea producing CO_2 increase, apprehension during arterial sampling causing hyperventilation, results of acute lactic acidosis, and effects of massive HCO_3- administration.

Using a diagrammatic representation prevents ambiguities in the analysis of acid-base data.

Renal Exchange Mechanisms

The classic work of Darrow and Yannet in 1935 showed, for practical purposes, that sodium, because of its high concentration and almost exclusive extracellular position, is the regulator of intracellular volume. Since the kidneys work exclusively on the extra-cellular plasma that is perfusing them, the regulation of body water and the size of fluid spaces are largely dependent on those factors that operate in the renal parenchyma to affect the volume and composition of the urine. In an average day, an adult taking in 2500 mL of fluid may lose as much as 1000 mL by extrarenal routes. With good renal blood flow, normal kidneys filter somewhere in the range of 170,000 mL of extracellular water through the glomeruli. More than 99 per cent of this water must be resorbed to form 1500 mL of urine. It should be recognized that with a normal intake of salt (about 10 gm) the resorption of sodium and chloride is also about 90 per cent complete. An oversimplified schema is shown in Figure.

The best hypothesis for the production of a hypertonic urine is that there is active "pumping" of sodium from the tubule lumen to the peritubular space. This, coupled with the passive diffusion of anions, establishes an osmotic force across the tubule that favors the diffusion of water in the same direction. Endocrine control of sodium resorption occurs in the distal convoluted tubule where finer adjustments are made. The body is able to conserve water efficiently by the secretion of antidiuretic hormone (ADH) or arginine vasopressin. ADH secretion from the neurohypophysis is triggered by osmoreceptors in the CNS, possibly located in or near the hypothalamic nuclei. Strong evidence exists for volume receptors, possibly in the left atrium and pulmonary veins. Hemorrhage has been shown to be a powerful stimulus to ADH release. According to the best contemporary studies, ADH allows the distal convoluted tubule and collecting tubule to become more water permeable, allowing water to move along osmotic gradients into the hyperosmolar medullary interstitium. In the

total absence of ADH, hypotonic urine in the range of 40 to 100 mOsm, is made. The effect of ADH on the mammalian kidney has been shown to involve the following steps:

1. ADH binds to receptor sites on the vascular-interstitial surface of collecting duct cells in both the cortex and the medulla.

2. The presence of the hormone on the receptor site activates the enzyme.

3. The activated adenylcyclase catalyzes the conversion of ATP to cyclic 3'5' AMP (the cAMP if degraded by phosphodiesterase).

4. Somewhere near the tubular membrane, the cAMP activates a C-AMP-dependent protein kinase.

5. A protein that is present on, or that interacts with, the cell wall of the tubular membrane surface of the tubule cell is phosphorylated, changing the cell wall protein configuration and enhancing permeability to water. In simplistic terms, the process punches a hole in the tubular membrane that lets water diffuse into the hypertonic renal interstitium.

For most of us in a normal state of hydration, ADH levels vary between 2 and 6 pg/mL. The maximum ADH effect is seen at 7 to 10 pg/mL. A mild painful stimulus raises levels to 30 to 40 pg/mL. A major operative procedure or increased intracranial pressure can raise levels to 400 to 1,000 pg/mL or higher. The duration varies with the stimulus.

In humans, a second hormonal agent, aldosterone, significantly affects sodium and water balance. A small dose (0.0045 microg/min) injected into an experimental preparation produces antidiuresis after a latent period of 1 hour. It enhances sodium resorption and causes increased potassium and hydrogen ion excretion. The distal convoluted tubule is one site of regulatory influence.

It has been the impression of the author that ADH release and aldosterone-like effects following average head and neck procedures are prominent but are very transient compared with a major thoracic or abdominal visceral procedure. The evidence is scanty, based on a failure to observe prolonged antidiuresis or prolonged sodium retention. ADH assays in several patients have confirmed the relationship. The half-life of endogenously excreted vasopressin is about 20 minutes. A prolonged response requires continued ADH secretion.

When the disorder in the neck or upper thorax may cause increased cerebral venous pressure, as in head trauma, or when both internal jugular veins are ligated, there may be a prolonged severe antidiuresis. The mechanisms are described under the heading of Acute Water Intoxication.

Clinical Fluid and Electrolyte Problems in Otolaryngology Patient

So far this chapter has touched briefly on physiologic points to serve as a refresher in some significant areas. The obvious question would be to ask how important are fluid management problems in the everyday practice of an otolaryngologist. The answer is "enough to cause problems". It seems that every surgeon who impairs the swallowing mechanism has

to discover "tube-feeding hyperosmolar, hypernatremic dehydration" for himself. At the other extreme, a nutritionally deprived elderly man with deglutition problems secondary to a tumor may be given an excess of water in the postoperative period, gain weight rapidly, and finally be pushed to pulmonary edema with a well-meaning colloid or volume load when he fails to put out sufficient urine. The ward physician fails to recognize a predictable ADH response to operative trauma. The problems arising from chronic starvation, difficult deglutition, electrolyte imbalance, and chronic systemic steroids are all somewhat characteristic of the specialty of otolaryngology. Even more of a challenge is the complicating medical problem. In 76 patients with carcinoma of the tongue seen on author's ward, the complicating diseases listed in Table 1 were noted.

Table 1. Major complicating diseases that were present preoperatively in 76 patients with carcinoma of the tongue

Peptic ulcer (bleeding, perforation or gastrectomy) in past	12
Cirrhosis (BSP > 25% or biopsy proved)	11
Heart disease (EKG proved infarct or valvular disease with failure)	6
Alcoholic neuropathy	5
Concurrent carcinoma	3
Active tuberculosis	3
Pernicious anemia	3
Hypertension	3
Other diseases (hospitalization)	5

The patients with peptic ulcers were usually thin and nutritionally deprived. This was particularly true when impairment of deglutition was associated with a small residual gastric pouch. The patient with cirrhosis occasionally retains large amounts of sodium in the postoperative period with concomitant edema formation. A patient with heart disease is unusually susceptible to misadventures that expand the extracellular volume. The patients with generalized arteriosclerosis, diabetes, previous obstructive uropathy, or chronic pyelonephritis do not have normal renal function. The number of effective nephrons may be marginal. Such patients do not have the same latitudes of water and electrolyte secretion as a healthy young person.

The message is simple. Many "average" cases already have complicated problems for total parenteral fluid maintenance without the changes induced by anesthesia, surgery, and surgical complications.

Individualized Approach to Fluid and Electrolyte Therapy

In checking over fluid and electrolyte misadventures in a teaching hospital, the most common cause of a problem is the unthinking application of a "formula" to the "routine" fluid orders hastily written on morning rounds. A "routine" order for a postoperative patient with moderate mitral stenosis may be something like "2500 cm D5W with 75 mEq NaCl per liter and 20 mL KCL per liter". This is topped off with a dash os come vitamin preparation containing ascorbic acid, and the fluid for the day is started without the physician's cerebral cortex having once been stirred by the process. Yet if you told the same physician that you were ordering the same 12 gm of salt in a diet for this same patient with mitral heart disease,

he would have fits of consternation. Having some secure "formula" or "routine order" to cling to seems to prevent any thinking about the patient's particular problems.

The most significant step that can be made in acquiring skills in fluid and electrolyte management is to recognize what peculiarities a patient may present that make *that* patient different from any other patient. One must consider the hormonal changes produced by surgery. One useful way of individualizing management is to use a fluid balance sheet. Much like music when you have practiced it long enough, the sheet itself no longer becomes necessary, and a rational method of thinking is established. In our cost-conscious age, a regular use of a balance sheet can avoid unnecessarily repetitious determinations of serum electrolytes. A format that I have found useful is shown in Figure. As seen in the figure, it can be constructed on any sheet of lined paper. Coupled with a few simple estimates of the electrolyte composition of the body fluids that may be lost, intelligent estimates can be made of net change. For information, a brief table (Table 2) is added as adapted from Gamble's (1964) data. These daily can be revised on the basis of laboratory determinations. In the patient with normal renal function and no complications, a number of assumptions can be made that simplify management. As we noted before, potassium excretion in the urine is relatively independent of volume and amounts to about 40 to 50 mEq per day. Modest excesses of K+ are well tolerated and excreted in the urine with no adverse effects. Unless the patient is secreting large amounts of acid gastric juice, the physician may estimate H+ and Na+ to be about equal in nasogastric (NG) suction. One must be alert for ambiguities such as may arise when an NG tube is threaded into the duodenum. The presence of bile in NG returns suggests that Na+ content may be higher as a result of the presence of duodenal secretions in the aspirate.

Fluid	Day 1			
	Volume	Na	K	Cl
Insensible	1000	-	-	-
Urine	1500	90	40	90
Nasogastric	750	45	10	70
T-tube	500	75	5	50
Ileostomy	250	35	5	25
Total Fluid loss	4000	245	60	235
Total fluid given	3000	225	60	285
Net difference	-1000	-20	0	+50
Lab values	WT 165 HCO_3- 25	135	45	101

For most practical purposes Na+ and Cl- content of the urine can be estimated at about 50 to 60 mEq/L of each, recognizing that the Na+ may be minimal during the time of aldosterone effect in the immediate postoperative period. On the other hand, it may be massive with salt loading.

Insensible water loss increases as body temperature increases. Osmotic work for the production of perspiration begins at about 37.8 °C (100 °F). It is hard to estimate the effect of the ambient ward environment, except by the physician's own response. A rule of thumb that is accurate enough for most practical purposes is that an average healthy afebrile 70 kg man loses about 600 mL of insensible water per day with no significant electrolyte content. A tracheostomy may reduce this slightly. Being on a respirator with full humidity further reduces insensible water loss to less than 200 mL/day. Insensible loss by sweating may be increased about 500 mL/24 hours for each degree of fever. (This presumes that the body temperature is constant over the 24 hours. A mental integration of the area under the temperature curve can be made to arrive at an estimate.) When active osmotic work is done by the sweat glands, the sodium and chloride content of sweat is in the range of 50 mEq/L. All these little generalities are nice for the uncomplicated adult patient. However, there are a number of problems that may occur on an ENT service that require more than average vigilance. In contemporary care in which team approach to oncology is used, the head and neck surgeon must adopt increased vigilance and be aware of the disorders his colleagues may produce. The use of *cis*-platinum infusion with vigorous mannitol diuresis is producing more frequent occurrences of severe iatrogenic hyponatremia. I have tried to select several instances that seem to pose the most frequent problems in otolaryngology patients. Reviewing the physiology of these problems may serve as a stimulus to reduce the occurrence of such errors and to pursue a study of other problem areas.

The Nutritionally Deprived

It is not uncommon to have to operate upon a thin, wasted patient giving history of a 20 to 30 pound weight loss. Significant weight loss follows impairment of deglutition in the oropharynx, esophageal obstruction, protracted sepsis, and numerous other disease entities. As the patient is first studied, a chronically low serum sodium level may be a prominent feature. Unlike acute dilutional hyponatremia, serum sodium levels in this chronic state are relatively well tolerated, even when the serum sodium hovers around 125 mEq/L. The dangers of management come from a narrow-minded focus on the serum sodium concentration alone. The inexperienced person will follow a reasoning cycle of: "low sodium --> give concentrated saline or salt". This eventuates in edema that further complicates the debilitated state. The problem is more complex. The real question is "Why is the extracellular sodium low?" In chronic starvation with weight loss, the energy sources must come from some fat and the lean body mass. The total body cell mass is depleted; both intracellular and extracellular protein are lost with depletion. Since intracellular protein contributes a significant portion of the *intracellular* osmotic activity, the total osmotic activity of the extracellular and intracellular environment is decreased. Figures for such a typical patient might reveal the following: Fat equal to less than 10 per cent of body weight. Serum Na+ = 130 to 135 mEq/L. Increased extracellular water. Increased intracellular water. Total body water = 80 per cent of the lean body mass when normally it should be about 70 per cent. Osmolality of plasma = 259 mOsm/L, when normal is about 290 mOsm. Total body potassium = 32 to 35 mEq/kg (exchangeable K) when the normal is about 45 to 46 mEq/kg.

Hyponatremia, *by itself*, impairs the kidney's ability to secrete a water load. Exogenously administered Na+ is distributed primarily in the extracellular water. Since the body osmolality is determined in this instance by the osmolality of the cell, there is an osmotic balance reestablished by water leaving the cell. This expands the extracellular fluid volume. If the amount of Na+ is sizeable, edema is produced, and the serum sodium level is still low. Treatment of this chronic low-sodium state is to restore a positive nitrogen balance by establishing alimentation, by parenteral supplementation, or by controlling septic processes. If acute edema has been produced in a starved patient with a low serum sodium level, the only recourse is to restrict water and to use mild diuretics to remove enough sodium to achieve a normal-sized extracellular water space.

Acute Water Intoxication

This is seen most commonly in the postoperative period either alone or in conjunction with some nutritional impairment. This problem requires the intervention of medical personnel for its production. In the postoperative period, vasopressin levels in the blood go from resting values of 2 to 5 microg/mL to as high as 50 to 750 microg/mL following a major operative procedure. ADH causes increased permeability of the distal tubule with the resultant transfer of water into the renal medullary interstitium. ADH levels usually stay elevated for 24 to 72 hours postoperatively following a major procedure such as a gastrectomy. There is a small amount of data concerning the ADH blood levels following oral and cervical surgical procedures. It has been the author's experience that ADH levels decline and that the hypertonicity of the urine usually fades by 48 hours after major ablative oropharyngeal and cervical surgery.

Clinical problems occur when a large water load is given to the debilitated patient while there is a significant ADH effect and the kidneys are unable to excrete the water load. Acute water intoxication is most commonly seen between 12 and 48 hours after surgery. When the serum sodium level is acutely lowered to 125 to 115 mEq/L, rapidly changing stupor, mental confusion, irrationality, and even generalized seizures may occur. One sure way of lowering the epileptic seizure threshold is to administer vasopressin and give water. In this circumstance body water is acutely diluted and osmolality is reduced.

Management is by one of two modes: First, give hypertonic sodium. This can be tolerated in a young, vigorous patient, but in an elderly patient with marginal cardiopulmonary reserve, an acute massive expansion of vascular fluid volume results. The second and more desirable method is water restriction. Water intoxication arises in the operating room and in the initial postoperative orders. Sensible fluid orders can prevent it.

There is a special circumstance that the author has observed in head and neck surgery in which severe water retention is a problem. When cerebral venous pressure is increased after ligation or obstruction of both internal jugular veins (as seen with a simultaneous bilateral neck dissection or with tumor occlusion in a superior vena caval obstruction), there is a marked ADH effect. Graphs of two such patients undergoing simultaneous bilateral neck dissections are shown in Figure. With the elevation of cerebral venous pressure, there is a marked antidiuretic effect (elevated urine osmolality with normal or reduced plasma osmolality). This antidiuresis persists until adequate venous collateral is developed. If such patients are inadvertently water loaded, severe dilutional hyponatremia and water intoxication

may supervene, as shown in Figure.

In the animal laboratory, dogs respond to elevated cerebral venous pressures in the same manner. The author has shown: (1) the average animal responds with antidiuresis at 18 cm H_2O, and 100 per cent of the animals respond at 25 cm H_2O; (2) the antidiuretic effect begins 20 minutes after pressure rise and persists as long (up to 3 hours) as cerebral venous pressure is elevated; and (3) the effect is directly related to elevated plasma arginine vasopressin levels.

In clinical practice, one must recognize that antidiuresis is produced by elevated cerebral venous pressures. Good management generally requires water restriction, as was done in the patients in Figure. Frequent plasma osmolalities must be determined to guide the administration of fluid. Lower urine volumes are to be expected.

The antidiuresis in head trauma victims has been known for years and documented.

Early Recognition of Acute Renal Failure

Therapeutic misadventures with excess water loads, excessive Na+ administration, and acute pulmonary edema are frequently a result of a faulty recognition of renal failure. Given a postoperative patient with oliguria, there are usually no good preoperative data on renal function (such as creatinine clearance). The pattern of disaster is typical. The patient is brought into the hospital before surgery for workup and diagnostic tests over a period of several days and nights and given nothing by mouth. The night of surgery, the patient is kept on nothing by mouth and given no supplementary hydration. He may receive variable amounts of fluid during surgery. Postoperative oliguria is noted. A misguided enthusiast gives 3 to 4 liters of fluids on the day of the patient's surgery with no results. This can be followed by a 500 mL water "flush" and topped off by colloids or, even worse, by an assortment of diuretics. The modern diuretics in and of themselves are not bad. However, if they are to be employed in attempting to convert a "low output" renal failure to a "high output" renal failure, they must be administered in a systematic progressive dosage schedule - after a clear diagnosis of acute tubular damage is made.

All these trial-and-error methods are pursued in an attempt to distinguish between acute tubular damage, ADH effect, simple dehydration, inadequate circulating blood volume, and chronic marginal renal function. By the time a clear answer is obtained, the patient has a fluid overload of 4 to 6 liters. What is a better approach? First, the clinical history: Try to pick out the patients with previous diseases suggesting renal involvement, i.e. pyelonephritis, diabetes, obstructive uropathy. Recognize those patients in whom there is a higher risk of renal damage as a result of blood loss, bacteremia, hypotensive episodes, and so forth. When oliguria is noted, the differentiation between dehydration or ADH effect and acute tubular necrosis is relatively simple. First of all, with simple dehydration there is maximal water conservation by functioning renal tubules. Serum osmolality is normal to elevated. The serum sodium level is normal to elevated. Urine osmolality is high - usually 600 to 900 mOsm/L - a clear separation between the concentrated urine and serum values. With acute tubular necrosis from any cause, the tubules do no osmotic work on the small amount of urine that is formed. Hence, it has the same osmolar values as an ultrafiltrate of plasma, i.e. about 300 mOsm/L. In the example of the water-loaded patient with oliguria, the serum sodium

concentration gives a clue. In a nondebilitated patient, a dilution of the extracellular water resulting from failure of free water excretion is reflected in a lowered serum Na level as well as a lowered osmolality.

Urine specific gravity determination is useful only when its many shortcomings are known. In acute tubular necrosis, the specific gravity is in the range of 1.010 *only* if no sugar is cleared, if there has been no evaporation of the specimen, if mannitol has not been given, if no dextran or hetastarch has been given, or if there is no proteinuria or hemoglobinuria. After administration of mannitol or dextran, specific gravity can be 1.040+ in the face of acute tubular necrosis. If there is a question of acute tubular damage, check the osmolalities. Modern apparatus has made this a simple determination that is available in most larger hospitals.

What steps can be taken to prevent acute tubular necrosis? First, avoid dehydration. Many studies have shown that the hydrated secreting tubule is less susceptible to the damage of transient hypoxemia and reduced renal blood flow. The patient scheduled for a major procedure should arrive in the operating room with an established water diuresis. Second, recognize and treat bacteremic episodes promptly. Third, treat hypotension promptly. Finally, when oliguria occurs, arrive at a definitive diagnosis early and begin active management before a patient has been pushed to pulmonary edema. Many times a patient can be managed without dialysis through a period tubular recovery *if* he has not had a fluid overload.

Tube Feeding Pitfalls

When a patient is unable to swallow and requires all feeding by gastrostomy or by a Levin tube, an unusual circumstance is established in which the internal environment is at the mercy of the intellect of his attending physician. He is unable to respond to thirst by drinking water. It should be unnecessary for every physician to discover iatrogenic hyperosmolar, hypernatremic dehydration for himself.

The normal adult on a 2000 calorie diet excretes about 60 gm of solid waste per day, which corresponds roughly to 1200 mOsm of solute. The load can be sharply increased if the diet is high in sodium. Thirty grams of urea will contribute about 500 mOsm, in which 30 gm of NaCl would contribute about 1200 mOsm/L. A rough calculation of solid load that a patient is receiving can be made from the following:

(Last 2 figures of specific gravity at 25 °C x 2.6 x 24 h urine vol)/1000 = Total solids in gm/day

When specific gravity is 1.020 and urine volume is 1000 mL the solids amount to:

20 x 2.6 x 1000/1000 = 52 gm/24 h

The figures in textbooks suggesting a maximum urine concentration to 1400 mOsm/L with water deprivation were obtained from healthy adults. In children, the maximum urinary concentration may approach only 800 mOsm/L. Similarly, older hospitalized patients rarely show an ability to concentrate urine above, 800 mOsm/L.

When high-calorie liquid feedings prepared from powdered concentrates are given to an adult in the concentration of 1 calorie per mL, a 2000 calorie diet is contained in much less than 1800 mL of water, even when the 300 mL of water of combustion is added. Commercial prepared liquid tube feedings vary from 410 mOsm to 800 mOsm. Insensible water loss then uses 500 to 600 mL of water. This leaves 1200 mL of water to excrete the obligatory osmotic load. Assuming a maximum ADG effect and no further aggravation of free water loss by hypotonic sweating, this would allow urine excretion at about 1000 mOsm/L. This degree of concentration can be achieved only with excellent kidney function. The problem can be aggravated further with tube feedings having a higher solute load because of the use of partially hydrolyzed products, soluble carbohydrates, and more electrolytes. The usual 2000 calorie, high-protein tube feeding produces about 1200 mOsm of solute that must be excreted. Heavier calorie loads push the osmotic load higher. It can be seen that if the osmotic load is high and the ability to concentrate urine is limited, there will be a deficit of water, which must be made up from the total body water, both intracellular and extracellular. Clinically the patient usually loses weight and becomes comatose and somnolent. Muscle weakness supervenes. Oral and respiratory mucous membranes are desiccated. Cough and respiration are impaired. Even if the condition is recognized, the patient is already in severe jeopardy. The most usual complication is pneumonia. *Prevention of the problem is the key to therapy.* When the patient is unable to augment his water needs by oral intake, adequate water volume must be provided with the feedings. Two approaches are satisfactory: First, never give tube feedings greater than 1/2 calorie per mL, or, second, give enough plain water by gastrostomy or tube (or IV as 5 per cent dextrose in water) to produce a net water excess; usually this is a volume approximately equal to the concentrated 1 calorie/mL feeding. When there is a question, keep urine diluted to under 500 mOsm/L. An understanding of this simple problem can prevent the frequently lethal complications that follow pushing a serum sodium concentration to 165 mEq/L.

A second problem follows the use of concentrated tube feedings, and this is a simple osmotic diarrhea. When more than 50 per cent of tube feeding calories are present as small carbohydrate molecules, they represent a large hyperosmolar load placed in the intestine. As the feeding is osmotically equilibrated by water transport into the gut, there is an intraluminal volume expansion. Thus, the carbohydrate, electrolyte, and other compounds act just as a saline cathartic, stimulating increased peristalsis and visceral emptying before balanced absorption is complete. The net effect is water, sodium, and bicarbonate loss as well as failure of nutritional absorption of the food introduced into the gastrointestinal tract. Again, the management consists of making these feedings nearer the osmolarity of body fluids, or making the feeding from more slowly hydrolyzed foodstuffs so that osmotic equilibration can occur slowly.

Adult Respiratory Distress Syndrome

This syndrome is not a fluid and electrolyte problem per se. Nevertheless, knowledge of the circumstances under which it may occur, its early recognition, as well as precise, judicious fluid management are essential for patient survival.

The syndrome is characterized by a delay in onset. It typically occurs 12 to 24 hours following injury, shock, and/or a successful resuscitative effort. This is a period when the clinician is confident of having surmounted the acute problems and when he or she may be

most complacent and least suspicious. Injudicious fluid loading at this time can ensure progressive pulmonary disaster. The clinician must *anticipate* that the syndrome may occur following any of the causative mechanisms listed in Table 3.

Table 3. Possible Causes of the Adult Respiratory Distress Syndrome

1. Septic shock:

a. Direct bacterial toxin endothelial damage

b. Causes listed below (2)

2. Extrathoracic trauma - etiologic theories include:

a. Pulmonary vasospasm --> increased pulmonary venous pressure --> pulmonary vascular capillary disruption

b. Circulating substance (vasoactive) released elsewhere in the body directly or indirectly increases pulmonary capillary permeability

c. Multiple microemboli (platelet aggregation)

3. Neurogenic pulmonary edema (frequent in head injury, CNS hemorrhage, CNS neoplasm, CNS infections):

a. Neurogenically controlled pulmonary arteriovenous (A-V) shunting

b. Eliminated by spinal cord section

c. Eliminated by pharmacologic systemic ganglionic blockade

4. Fat embolism

5. Pulmonary contusion

6. Penetrating lung injuries

7. Inhalation of hot gases or bronchial burn

8. Oxygen toxicity

9. Massive blood transfusion

The early phase is characterized by bilateral patchy pulmonary infiltrates that may resemble mild pulmonary edema on chest x-ray studies. If one could observe the lung at this stage, pulmonary capillary and venous engorgement, microhemorrhages, and an increase in interstitial tissue fluid would be noted. Blood gas analysis shows a PaO_2 less than 60 torr. The $PaCO_2$ remains low, in the range of 35 to 45 torr. In the early phases, the syndrome is best

characterized by a low arterial O_2 out of proportion to the patient's clinical symptoms. By any means of measurement, there is an increasing pulmonary venous admixture, i.e. shunt fraction. This is a measure of the perfused lung with decreased areas of ventilation and impaired A-a diffusion. Space does not permit lengthy discussion, but the interested reader is referred to the fine discussion by Laver in the first chapter in Sabiston and Spencer (1976).

If the syndrome progresses, there is increasing pulmonary infiltrate, increasing pulmonary density, and decreased arterial PaO_2, event with supplemental O_2 and respiratory support. Lactate levels increase. Pulmonary compliance measurements show increasing "stiffness" of the lungs. If volume-cycled respiratory assistance is employed, higher and higher pressures are required to maintain adequate tidal volume. Pneumothorax and its attendant complications may occur.

Although patients in trauma and burn centers and orthopedic wards and those undergoing thoracic surgery are more often affected, the otolaryngologist is not excused from dealing with the respiratory distress syndrome. Head and facial injuries, multiple fractures, central nervous system (CNS) infection, sepsis, and hypotensive episodes are all within the domain of the otolaryngologist. The common factor in all of the etiological causes is the production of pulmonary capillary vascular injury, with the consequent increase in permeability or microvascular hemorrhage, or both.

The management remedies are few and are aimed at (1) maintaining adequate oxygenation and respiratory support until there is resolution and restoration of pulmonary capillary integrity, (2) minimizing interstitial extravasation of fluid and blood elements, and (3) possible reduction of further pulmonary vascular injury.

The key therapy is suspicion that pulmonary capillary damage may have occurred. Document the reduced O_2 level. Monitor the blood gases and recognize that a falling PaO_2 may be the earliest reliable clue. Carefully avoid fluid overloading. Typically, the syndrome can and does occur in the face of a normal or low central venous pressure (CVP). If the syndrome is suspected, fluids should be curtailed to equal insensible loss plus output. If the patient is overloaded, total fluid restriction can be employed. If PaO_2 is falling rapidly, infiltrates are increasing, or the PaO_2 is under 50 torr, additional oxygen and volume-cycled respiratory assistance are used to keep PaO_2 levels at 55 to 65 torr or better. Levels of inspired O_2 above 40 per cent should be used only as needed. One should attempt to keep levels of inspired O_2 above 80 per cent for less than 12 to 24 hours or only as absolutely required.

Preinjury administration of anti-inflammatory steroids has been of benefit in experimental studies. Postinjury administration has not been effective. It is uncertain whether systemic steroids have any use in clinical circumstances.

The key to patient survival remain: (1) early suspicion and recognition, (2) avoidance of fluid overload in the vulnerable patient, (3) precise control of respiratory support for the duration of the pulmonary capillary injury, and (4) administration of antibiotics to minimize bacterial superinfection in the atelectatic areas.

Patients Who Retain Salt and Water

The response of surgical patients to trauma by excretion of aldosterone is magnified in several conditions. Two examples are cirrhosis of the liver and congestive heart failure. The more sensitive patients are those with rheumatic valvular disease of the left ventricle.

In cirrhotic patients, particularly those with ascites, there are many empirical data and a confusion of opinion. The term "hepatorenal syndrome" has been used to place the patient in a category without explaining mechanisms. The cirrhotic patient's predilection to retain salt and water can stem from lowered renal glomerular filtration rate, increased antidiuretic activity, altered permeability of membranes, and altered tubular sodium resorption associated with increased aldosterone secretion. The fact is, sodium is retained. It produces an iso-osmolar expansion of extracellular volume. There is probably some "secondary" aldosteronism resulting from an inability of the damaged liver to inactivate circulating aldosterone.

The second large group of patients who require vigilance in management are those who have congestive heart failure, who have had this in the past, or who have such marginal cardiac reserve that they can be converted easily to congestive failure by minimal blood volume expansion. Several factors may be operating to produce the salt and water retentions. These factors are diagrammed in Figure.

In the patient with congestive heart failure, there is a total body excess of sodium. This sodium may be within cells as well as in the extracellular fluid. There may also be a deficit of cell potassium. Which of the several mechanisms is dominant is uncertain. Nevertheless, the practical message is clear - more sodium is retained in a patient with congestive heart failure, and an excess sodium load is not excreted as well.

Hypercalcemia

Epidermoid squamous cell cancer in the head and neck can increase serum calcium by two mechanisms. (1) There can be direct secretion by the cancer of substances that produce parathormone-like effects. (2) Metastases to bone can cause rapid mobilization of bone calcium stores, thus elevating the serum level. Elevated serum calcium as cause of primary paraneoplastic syndrome without systemic metastasis is rare. Goodwin and Chandler (1976) found it in only two of 307 patients with head and neck epidermoid cancer. After tumor resection, they had persistently normal calcium levels. Subsequent autopsy demonstrated absence of metastases and normal parathyroid glands. In this same series, 139 of the 307 patients developed metastases. Ten of 139 (7 per cent) developed hypercalcemia. In studying these patients, half were thought to have hypercalcemia due to rapid release from invaded bone. The other half were thought to have tumors that secreted parathormone-like substances. We must conclude that calcium elevation is not always associated with extensive bone or systemic metastases. The likelihood is about 50%.

Hypercalcemia above 12 microgm/dL produces a prominent muscle weakness and malaise. At 13 to 14 microgm/dL, nausea, vomiting, and severe muscle weakness occur. Coma and respiratory depression can occur at serum calcium levels over 15 microgm/dL. Levels at or above 15 microgm/dL are a true medical emergency.

All patients with hypercalcemia should be treated with hydration and diuretics. Lowering the calcium increases their well-being. Effective treatment of the cancer is the best approach. Where there are extensive bone metastases, steroids sometimes lower calcium levels. With advanced neoplasms, mithramycin has been used successfully. However, mithramycin is a potent, toxic, last therapeutic resort. The physician must monitor the blood elements, platelets, and leukocytes as well as the prothrombin time and/or partial prothromboplastin time. A slight decline of platelets or elevation of prothrombin time requires that the administration of the drug be stopped.