

Module 2.6

Fluid Balance and Metabolism in Surgery

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Learning objectives

- To understand the basics of fluid and electrolyte balance;
- To appreciate the close link between nutrition and fluid and electrolyte balance;
- To appreciate how normal fluid and electrolyte physiology is modified by illness and injury;
- To understand the principles of fluid prescription;
- To be aware of the adverse clinical consequences of errors in prescription;
- To appreciate methods of diagnosis and monitoring and the importance of serial data recording;
- To appreciate that, in nutritional prescriptions, the fluid and electrolyte content is of vital importance.

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Key Messages

- The intake, absorption, and physiology of fluid and electrolytes are inseparable from nutrition;
- Education, training and practice in fluid and electrolyte balance have been poor. This has led to a great deal of iatrogenic and avoidable morbidity and mortality as well as increased costs;
- Normal fluid and electrolyte physiology and the pathological changes, which accompany the responses to injury and illness, need to be understood in order to avoid errors in prescribing. Both over- and under-treatment have serious clinical consequences;
- The uses and limitations of the parameters used for diagnosis and monitoring should be well understood and used in a critical manner. The data obtained should be serially recorded in an accurate, clear and easily accessible manner. Daily weighing is the only satisfactory bedside method of measuring water balance;
- Prescriptions of fluid and electrolytes should be carried out by, or under the guidance of, experienced and knowledgeable staff;
- Each unit should have clear protocols and guidelines for fluid and electrolyte management and the staff should be trained in these.

1. Introduction

The monitoring and prescribing of fluids in patients necessitates a good practical understanding of normal and abnormal physiology and of the requirements of patients under different circumstances. This chapter is designed to help in this task. Unfortunately, several studies have shown that knowledge and practice of fluid and electrolyte balance is poor among doctors causing increased morbidity and mortality among patients (1-6). In fact, most clinical problems in this field are straightforward and can be managed using a few basic principles. This chapter will outline the approaches to fluid and electrolyte management and will not attempt to cover all the many different clinical circumstances that may be encountered. We aim to equip the reader with the basic knowledge to analyse and understand fluid and electrolyte problems and to play a constructive part in their management.

2. Definitions

For those whose school biology and chemistry are a distant memory it may be helpful to revise a few definitions.

Anabolism – the synthesis of large molecules from small ones, e.g. protein from amino acids or glycogen from glucose.

Catabolism – the breakdown of large molecules into small ones, e.g. protein to amino acids or glycogen to glucose.

Solution – fluid consisting of a solvent, e.g. water, in which a soluble substance or solute, e.g. sugar or salt, is dissolved.

Salt – In a strict chemical sense this means any compound produced by reaction between an acid and an alkali, but it is used colloquially in medicine to mean one particular salt, sodium chloride (NaCl), produced by the reaction between hydrochloric acid and sodium hydroxide. Throughout this chapter, the term will be used in that sense.

Electrolyte – a substance whose components dissociate in solution into positively (cation) and negatively (anion) charged ions. For example, Sodium Chloride, in solution, dissociates into Na^+ and Cl^- . Other electrolytes of physiological importance include Ca^{2+} , Mg^{2+} , K^+ , PO_4^{2-} , etc. Glucose is not an electrolyte since it does not dissociate in solution. At all times the total number of positive charges balances the number of negative charges to achieve electrical neutrality.

Osmosis – this describes the process by which water moves across a semi-permeable membrane (permeable to water but not to the substances in solution) from a weaker to a stronger solution until the concentration of solutes are equal on the two sides. This force

is termed osmotic pressure or, in the case of colloids e.g. albumin, oncotic pressure. It is proportional to the number of atoms/ions/molecules in solution and is therefore a correlate of mmols/litre or /kg solution and is expressed as mOsm/litre (osmolarity) or mOsm/kg of solution (osmolality). In clinical chemistry the term 'osmolality' is the one most often used. For example, out of approximately 280-290 mOsm/ kg in extracellular fluid the largest single contributor is sodium chloride. This dissociates in solution and therefore its component parts Na^+ and Cl^- exert osmotic pressure independently i.e. Na^+ (140 mmol/kg), contributes 140 mOsm, and Cl^- (100 mmol/kg) contributes 100 mOsm/l. Additional balancing negative charges come from bicarbonate (HCO_3^-) and other anions. In the intracellular space potassium (K^+) is the predominant cation (see below). Because glucose does not dissociate in solution, each molecule, although much larger than salt, behaves as a single entity in solution and at a concentration of 5 mmol/kg, contributes only 5 mOsm/kg in total. The cell membrane and the capillary membrane are both partially permeable membranes although not strictly semi permeable in the chemical sense (see below). They act, however, as partial barriers dividing the extracellular (ECF) from the intracellular fluid (ICF) space, and the intravascular from the interstitial space. Osmotic or oncotic shifts occur across these membranes, modified by physiological as well as pathological mechanisms.

Crystalloid – a term used commonly to describe all clear glucose and/or salt containing fluids for intravenous use, e.g. 0.9% saline, Hartmann's solution, 5% dextrose, etc.

Dehydration – the subject of fluid and electrolyte balance is bedevilled by loose terminology leading to muddled thinking, incorrect prescription, and adverse clinical consequences. The term 'dehydration' strictly means lack of water, yet it is also used colloquially to mean lack of salt and water or even more loosely to describe intravascular volume depletion. The terms 'wet' and 'dry' are applied to patients with similarly imprecise meaning. We make a plea for confining the use of dehydration to mean 'water lack' and for using unambiguous terms such as 'salt and water depletion', 'blood loss', 'plasma deficit', and so forth, since these are clear diagnoses indicating logical treatments.

3. Normal Anatomy and Physiology

The body of an average adult is 60% water, although the percentage is lower in obesity, since adipose tissue has a low water content compared with lean tissue (7). As shown in **Fig. 1**, the total body water is divided functionally into the extracellular (ECF=20% of body weight) and the intracellular fluid spaces (ICF= 40% of body weight) separated by the cell membrane with its active sodium-potassium pump, which ensures that sodium remains largely in the ECF. The cell, however, contains large molecules such as protein and glycogen, which cannot escape and therefore draws in K^+ ions to maintain electrical neutrality (Donnan Equilibrium). These mechanisms ensure that Na^+ and its balancing anions, Cl^- and HCO_3^- , are the mainstay of ECF osmolality, and K^+ has the corresponding function in the ICF.

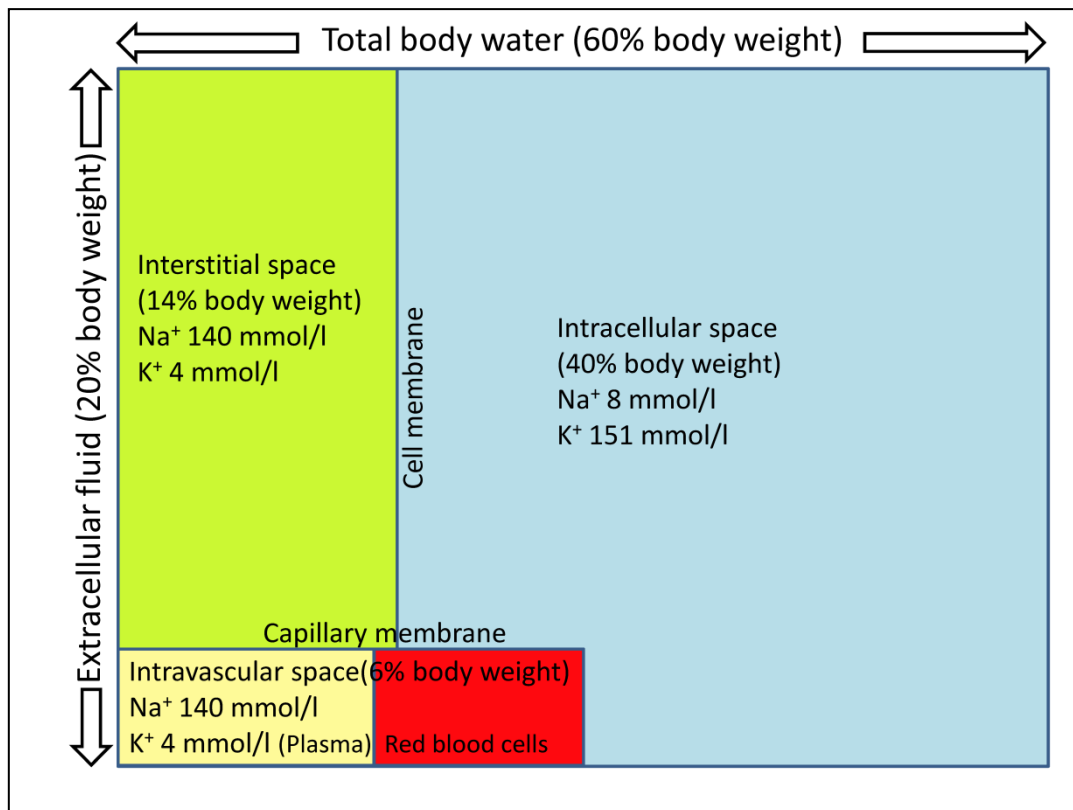


Fig. 1 Anatomy of the body fluid compartments

The extracellular space is further divided into the intravascular (within the circulation) and the interstitial (extravascular fluid surrounding the cells) fluid spaces. The intravascular space (blood volume = 5-6% of body weight) has its own intracellular component in the form of red (haematocrit = 40-50%) and white cells and an extracellular element in the form of plasma (50-60% of total blood volume). The intravascular and extravascular components of the ECF are separated by the capillary membrane, with its micropores, which allow only a slow escape rate of albumin (5%/hr)(8), which is then returned to the circulation via the lymphatics. While the hydrostatic pressure within the circulation tends to drive fluid out, the oncotic pressure of the plasma proteins, e.g. albumin, draws fluid in and maintains the relative constancy of the plasma volume as a proportion of the ECF (Starling effect).

There is also a clinically important flux of fluid and electrolytes between the ECF and the gastrointestinal (GI) tract involving active secretion and reabsorption of digestive juices (**Fig. 2**). In health there is a constant flux between these various spaces and important physiological mechanisms ensure a constant relationship between them, which we may term the *internal fluid balance*.

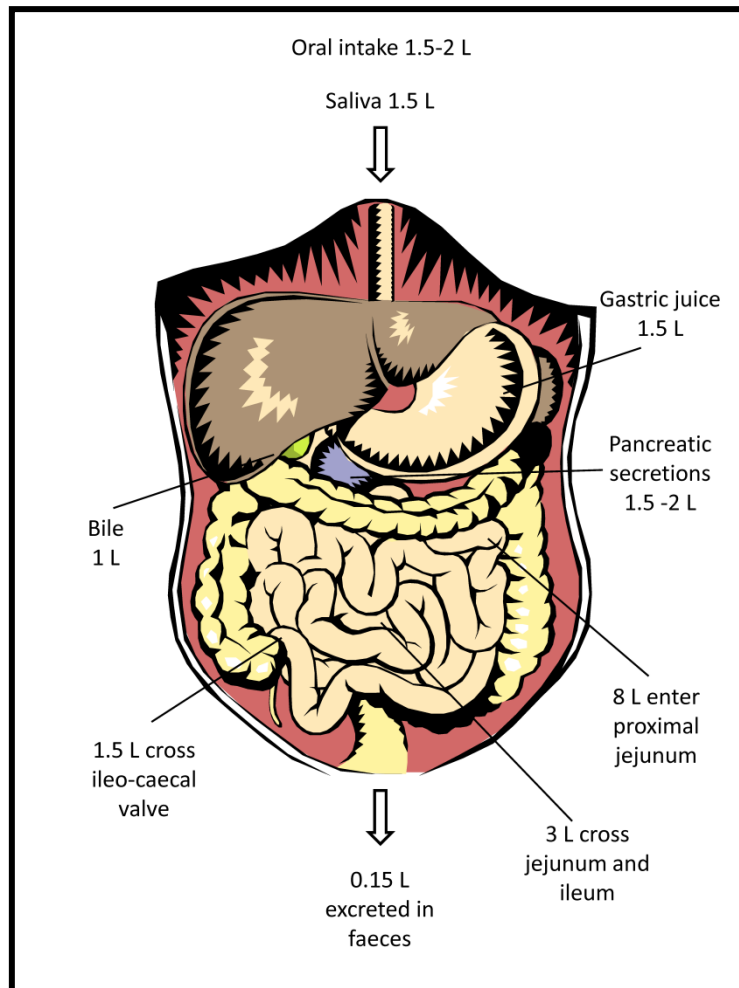


Fig. 2 Fluid flux across the gastrointestinal tract

The *external fluid and electrolyte balance* between the body and its environment is defined by the intake of fluid and electrolytes versus the output from the kidneys, the gastrointestinal tract, and the skin and lungs (insensible loss). Since the external and internal balances may be disturbed by disease, it is important to understand normal physiology in order to appreciate the disorders, which may occur in patients.

3.1. External Balance

Values for the normal daily intake and output of fluid and electrolytes are shown in **Tables 1 and 2**. These are only an approximate guide and may have to be modified in the presence of excessive losses, e.g. of water and salt through increased sweating and insensible loss in hot climates. They may also need to be modified in the presence of disease, e.g. gastroenteritis which causes abnormal losses of fluid and electrolyte from the GI tract (**Fig. 2 and Table 3**).

Table 1
Daily water balance

Intake (ml)		Output (ml)	
Water from beverages	1200	1500	Urine
Water from solid food	1000	900	Insensible losses from skin and lungs
Metabolic water from oxidation	300	100	Faeces

Table 2
Normal maintenance requirements

Water	25-35 ml/kg/day
Sodium	0.9-1.2 mmol/kg/day
Potassium	1 mmol/kg/day

Table 3
Approximate electrolyte content of gastrointestinal and skin secretions

Secretion	Na ⁺ (mmol/L)	K ⁺ (mmol/L)	Cl ⁻ (mmol/L)
Saliva	40	20	40
Gastric juice	70-120	10	100
Bile	140	5	100
Pancreatic juice	140	5	75
Small intestine	110-120	5-10	105
Diarrhoea (adult)	120	15	90
Sweat	30-70	0-5	30-70

3.2. Intake

Under normal circumstances most of our fluid intake is oral, but remember that all food contains some water and electrolytes and also that water and CO₂ are end products of the oxidation of foodstuffs to produce energy. This metabolic water is a small but significant contribution to net intake. Our drinking behaviour is governed by the sensation of thirst, which is triggered whenever our water balance is negative through insufficient intake or increased loss. It may also be triggered by a high salt intake, which necessitates the intake and retention of extra water in order to maintain the ECF sodium concentration and osmolality in the normal range. Although, in the elderly, the thirst mechanism becomes blunted, it ensures, on the whole, that our intake matches the needs of bodily functions, maintaining a zero balance in which intake and output are equal and physiological osmolality is maintained.

More than a century ago the great French physiologist Claude Bernard coined the term '*volume obligatoire*' to describe the minimum volume of urine needed to excrete waste products e.g. urea, in order to prevent them accumulating in the blood. This concept implies that, if sufficient fluid has been drunk or administered to balance insensible or other losses and to meet the kidney's needs, there is no advantage in giving additional or excessive volumes. Indeed, excessive intakes of fluid and electrolytes may be hazardous under certain circumstances (see below) and overwhelm the kidney's capacity to excrete the excess and maintain normal balance. Salt and water retention causes oedema, which only becomes clinically apparent when the ECF has been expanded by at least 2-3 litres.

3.3. Output

- 1) **Insensible loss:** evaporation of water from the lungs and skin occurs all the time without us being aware of it. In our temperate climate the amount so lost is 0.5-1 litre/day. In a warm environment, during fever, or with exertion, we produce additional sweat containing up to 50 mmol/l of salt.
- 2) **GI losses:** normally, the intestine absorbs water and electrolytes very efficiently so that fluid loss in the stool is as little as 100-150 ml/day, although, in the presence of disease this may be greatly increased (**Table 3 and Fig. 2**).
- 3) **Kidney:** this is the main organ for regulating fluid and electrolyte balance as well as excreting the waste products of metabolism e.g. urea. In this function, its activity is controlled by pressure and osmotic sensors and the resulting changes in the secretion of hormones. The modest daily fluctuations in water and salt intake cause small changes in plasma osmolality which trigger osmoreceptors. This in turn causes changes in thirst and also in renal excretion of water and salt. If blood or ECF volumes are threatened by abnormal losses, volume receptors are triggered (see below) and override the osmoreceptors. In the presence of large volume changes, therefore, the kidney is less able to adjust osmolality, which can be important in some clinical situations.

(a) Water

Organs, which sense the changes in osmolality of plasma (osmoreceptors), are located in the hypothalamus and signal the posterior pituitary gland to increase or decrease its secretion of vasopressin or antidiuretic hormone (ADH). Dilution of the ECF, including plasma, by intake of water or fluid of osmolality lower than plasma, causes ADH secretion to fall, so that the distal tubules of the renal glomeruli excrete more water and produce a dilute urine. Conversely, dehydration causes the ECF to become more concentrated, ADH secretion rises and the renal tubules reabsorb more water, producing a concentrated urine. In response to dehydration, the normal kidney can concentrate urea in the urine up to a hundred-fold, so that the normal daily production of urea during protein metabolism can be excreted in as little as 500 ml of urine. In the presence of water lack, the urine to plasma urea or osmolality ratio is, therefore, a measure of the kidney's concentrating capacity. Age and disease can impair the renal concentrating capacity so that a larger volume of urine is required in order to excrete the same amount of waste products. Also if protein catabolism increases due to a high protein intake or increased catabolism, a larger volume of urine is needed to clear the resulting increase in urea production. To assess renal function, therefore, measurement of both urinary volume and concentration (osmolality) are important, and the underlying metabolic circumstances taken into account. If serum urea and creatinine levels are unchanged and normal, then, urinary output over the previous 24 hours has been sufficient, fluid intake has been adequate, and the urinary '*volume obligatoire*' has been achieved.

(b) Sodium

Since the volume of the ECF and its percentage of the total body water are largely dependent on the osmotic effect of Na^+ and its accompanying anions, it is important that the kidneys maintain Na^+ balance within narrow limits. If salt depletion occurs, then the ECF, and with it the plasma, volume falls. Pressure sensors in the circulation are then stimulated and these excite renin secretion by the kidney. This, in turn, stimulates aldosterone secretion by the adrenal gland, which acts on the renal tubules, causing them to reabsorb and conserve Na^+ . Conversely, if the intake of Na^+ is excessive, the renin-aldosterone system switches off, allowing more Na^+ to be excreted, until normal balance is restored. The mechanism for salt conservation is extremely efficient and the kidney can reduce the concentration of Na^+ in the urine to <5 mmol/l. On the other hand, even in health, we are slow to excrete an excess salt load. In studies on normal subjects given infusions of 5% dextrose or 0.9% saline, a water load was excreted within 2 hours, whereas 60% of a salt load was still retained after 6 hours.

The mechanism for maintaining sodium balance may become disturbed in disease, leading to Na^+ deficiency or, more commonly, to excessive sodium retention, with consequent oedema and adverse clinical outcome.

(c) Potassium (K^+)

Although only a small proportion of the body's K^+ is in the extracellular space, its concentration has to be maintained within narrow limits to avoid potentially fatal cardiac events or muscular dysfunction. This is achieved by exchange of K^+ in the renal tubules for Na^+ or H^+ , allowing more or less K^+ to be excreted. In the presence of K^+ deficiency, H^+ ion reabsorption is impaired, leading to hypokalaemic alkalosis.

4. Acid-base Balance

Only a brief outline will be given here. For more detail the reader is referred to the appropriate text (9). The degree of acidity or alkalinity is described by the term pH, reflecting the concentration of hydrogen ions (H^+). For optimal organ function it has to be kept within a narrow range around 7.4. Acidosis is described as a fall in pH below this value and alkalosis a rise above it. Three organs play an important role in the control of pH:

- 1) **the lungs** which blow off CO_2 , controlling the amount of carbonic acid in the blood. In lung ventilatory failure, CO_2 and hence carbonic acid accumulate in the blood. This is called respiratory acidosis. Blood gas analysis reveals a low pH, a high pCO_2 , and a normal or slightly elevated bicarbonate. (In prolonged CO_2 retention the body attempts to restore pH to normal by retaining alkali in the form of bicarbonate).
- 2) **the liver** converts lactic acid, produced by anaerobic respiration in muscle, back to glucose (gluconeogenesis). Accumulation in the blood of lactic acid due to anoxia, circulatory failure (shock) or liver failure causes a metabolic acidosis. In this situation pH falls, bicarbonate is low, and pCO_2 falls as the lungs attempt to raise pH by blowing off more CO_2 .
- 3) **the kidney** excretes organic acids and, in its distal tubules exchanges H^+ for K^+ and Na^+ . In renal failure therefore, organic acids accumulate, H^+ exchange is impaired and another form of metabolic acidosis is created.

A number of pathological conditions, as well as those mentioned, also affect acid base balance e.g. diabetic ketoacidosis, loss of acid (stomach) or bicarbonate (pancreas, small bowel) from the GI tract, as well as a number of less common problems.

The treatment of acid base problems is first and foremost that of the underlying condition e.g. improving the circulation, correcting hypovolaemia, relieving hypoxia, treating renal failure, regaining diabetic control with insulin, etc. In severe acidosis, $pH < 7.0$, it may sometimes be necessary to administer bicarbonate.

5. Pathophysiology

Diseases such as gastroenteritis, diabetic ketoacidosis or Addison's disease cause their own specific changes in fluid and electrolyte balance, but there are non-specific changes which occur in response to any form of injury or inflammation, which have important implications for management, particularly of surgical patients.

5.1. Response to Injury

In the 1930's, Cuthbertson (10, 11) described the metabolic changes, which occur in response to injury, as an increase in metabolic rate and protein breakdown to meet the requirements for healing. These changes were later shown to be due to neuroendocrine and cytokine changes and to occur in three phases. The ebb or shock phase is brief and modified by resuscitation. This gives way to the flow or catabolic phase, the length and intensity of which depends on the severity of injury and its complications. As inflammation subsides, the convalescent anabolic phase of rehabilitation begins. In parallel with these metabolic changes there are changes in water and electrolyte physiology. During the flow phase, there is an increase in ADH and aldosterone secretion leading to retention of salt and water with loss of potassium. These changes are exacerbated by any reduction in blood or ECF volume. The normal, if somewhat sluggish, ability to excrete an excess salt and water load is suspended, leading to ECF expansion

and oedema. The response to injury also implies that oliguria is a normal response to surgery, and does not necessarily indicate the need to increase the administration of salt and water or plasma expanders unless there are also indications of intravascular volume deficit e.g. from post operative bleeding. Salt and water retention after injury can be seen as nature's way of trying to protect the ECF and circulating volume at all costs. It also explains why sick patients can be so easily overloaded with excessive salt and water administration during the flow phase. Since water as well as salt is retained, it is also easy to cause hyponatraemia by giving excess water or hypotonic fluid. It is important, therefore, to administer crystalloids, not only in the correct volume but also in the appropriate concentration. In the presence of the response to injury, the kidneys are unable to correct for errors in prescribing.

The convalescent phase of injury is not only characterised by the return of anabolism but also by a returning capacity to excrete any excess salt and water load that has been accumulated. These periods have been termed the '*sodium retention phase*' and the '*sodium diuresis phase*' of injury.

5.2. Potassium

K⁺ losses after injury are not only secondary to increased excretion, but also to protein and glycogen catabolism. As intracellular protein is broken down and its constituent amino acids are released from cells, so intracellular negative charges are lost and K⁺, with its balancing positive charges, passes out into the ECF to be excreted. In situations where catabolism is extreme and renal function is impaired, the outflow of K⁺ from the cells may exceed the kidney's capacity to excrete it, causing dangerous hyperkalaemia. Conversely, in the convalescent phase, as net intracellular protein and glycogen anabolism is restored, the cells take up K⁺ again and the patient's potassium intake has to be increased or else hypokalaemia will develop.

5.3. Intra- vs. Extravascular Fluid

The intra- and extra-vascular components of the ECF are separated by the capillary membrane, with its micropores, which allows only a very slow escape of the molecules, such as albumin, which create the oncotic pressure of plasma. In health, albumin escapes at a rate of 5% per hour and is returned to the circulation from the interstitial space via the lymphatics and the thoracic duct. In fact the escape rate is much higher in some organs, e.g. the liver, than in others (9). The rate is also increased in disease. At any one time, the amount of albumin in the extravascular space (170 g) is more than in the intravascular space (140 g), and the flux between them is 10 times the rate of albumin synthesis. For these reasons the serum albumin concentration is affected faster and to a greater degree by the physical effects of redistribution and dilution than by any nutritional or metabolic effects on synthesis or breakdown (12, 13) (**Figs. 3 and 4**).

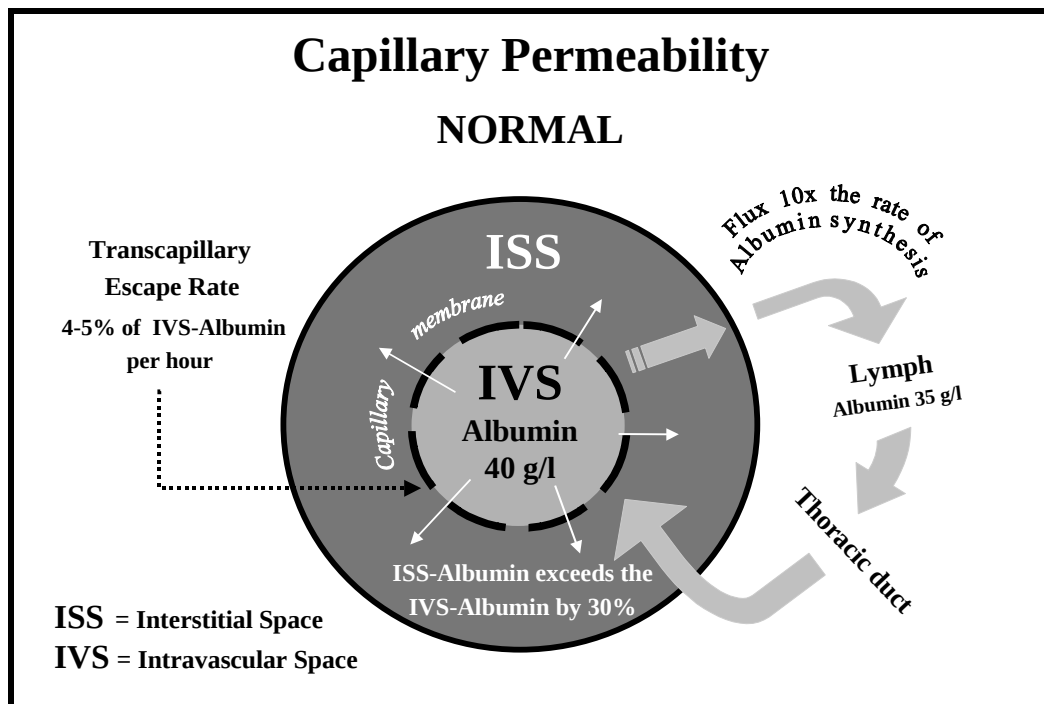


Fig. 3 Capillary permeability and albumin flux in health

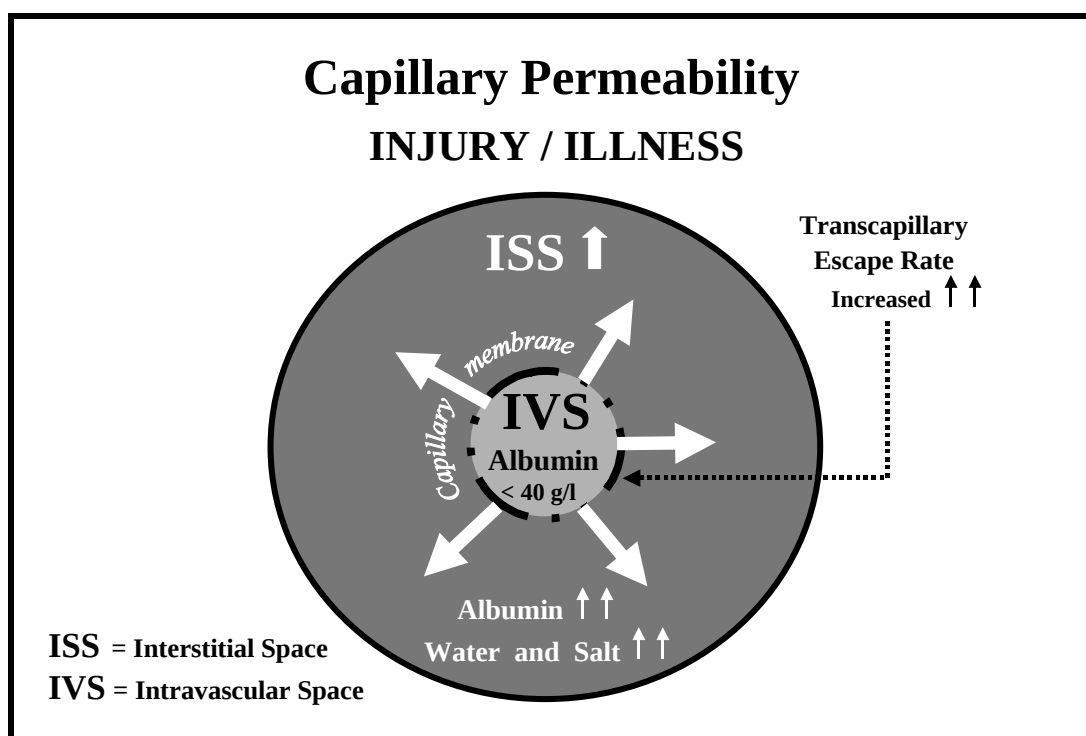


Fig. 4 Capillary permeability and albumin flux in illness and after injury and stress

The equilibrium between the two compartments is determined by the capillary membrane pore size, the relative concentration and hence oncotic pressure on the two sides of the membrane, and the difference in hydrostatic pressure across the membrane. This relationship is described by the Starling equation (14), which indicates that the flux of fluid across the membrane is inversely related to capillary oncotic pressure as long as other factors in the equation remain constant.

$$F_{H_2O} = KC \times SA [(P_c - P_i) - (OP_i - OP_c)]$$

where F_{H_2O} is the flux of water across the capillary, KC the capillary hydraulic conductivity, SA the capillary surface area, P_c the capillary hydraulic pressure, P_i the interstitial hydraulic pressure, OP_i the interstitial oncotic pressure and OP_c the capillary oncotic pressure.

The flux of albumin of 5%/hr is a whole body average, but the balance of Starling forces varies between tissues. Although the pulmonary and hepatic microcirculations have a lower hydrostatic pressure, their permeability to proteins is much greater than in other tissues such as muscle (9) so that transudate is more likely to develop in the splanchnic and pulmonary circulations than elsewhere.

5.4. Response to Starvation and Refeeding

Starvation: In the famous studies by Keys et al (15), normal male volunteers were subjected to semi-starvation for 24 weeks and lost 23% of their body weight. During this period, in which fat and lean mass were lost, the ECF rose as a percentage of body weight. More severe cases of starvation with losses of up to 40% of body weight, were studied by the Jewish physicians in the Warsaw ghetto during the second world war (16). Among other features, they described the extreme degrees of fluid retention experienced by these individuals who exhibited '*famine oedema*'. Many of their patients were also suffering from infections and therefore showed the combined effects of starvation and the response to injury. This is also seen during tropical famines, when some children develop *marasmus* without oedema, and others, with possibly greater injury responses to infections and parasites as well as exposure to salt and water, show *kwashiorkor*.

Refeeding: Apart from severe thiamine deficiency, necessitating thiamine supplementation to avoid precipitating Wernicke's encephalopathy, the *refeeding syndrome* mainly involves fluid and electrolytes (17).

(a) **With severe cachexia** i.e. BMI<15, as in severe anorexia nervosa or famine conditions, water and sodium intolerance leads to refeeding oedema and even heart failure, unless these are restricted in the early stages of refeeding. It has also been shown that carbohydrate refeeding in particular, enhances salt and water retention (18, 19). Many of the cachectic inmates of concentration camps, after the second world war, suffered from this problem following release, and many died as a result.

(b) **As discussed** elsewhere in this module, the rapid cellular uptake of K^+ and PO_4^{2-} following refeeding may precipitate dangerously low levels of these electrolytes unless they are routinely and adequately supplemented and monitored and calories, particularly carbohydrate are introduced slowly. Serum Mg should also be monitored and supplemented as necessary.

Recommendations for the prevention and treatment of refeeding syndrome have been published elsewhere (17).

6. Other Minerals and Electrolytes in Health and Disease

6.1. Magnesium

Magnesium is distributed mainly in bone (500-600 mmol) and intracellular fluid (500-850 mmol). Only 12-20 mmol is present in the extracellular fluid at a normal concentration of 0.7-1.2 mmol/l. Mg, like Ca is bound to albumin in the circulation and a low serum level must therefore be interpreted in the light of changes in serum albumin concentration. It is an important component of many enzyme systems and is essential for membrane stability (Na^+ , K^+ ATPase) In the presence of a moderately low magnesium (0.4-0.6 mmol/l) the patient may feel less well, more lethargic, and with diminished muscle strength, although it is surprising how levels around 0.5 are tolerated. Nonetheless restoration of normal levels is associated in an improvement in wellbeing. At lower levels, there is neuromuscular irritability and, in severe cases, convulsions. Peripheral

vasodilatation and cardiac arrhythmias may also occur. A fall in free magnesium concentration causes secondary effects on calcium metabolism, with lowered parathyroid (PTH) levels and hypocalcaemia. All hypocalcaemic patients should therefore have a serum Mg measured and corrected if this is the primary problem. If this is done, PTH levels rise to normal with consequent restoration of the serum Ca to normal (20).

The physician is most likely to encounter hypomagnesaemia in gastro intestinal (GI) disease where there are persistent and prolonged losses of GI fluids, e.g. inflammatory bowel disease or short bowel. The Mg concentration in the upper small bowel is only 1 mmol/l, which rises in the more distal bowel, so that losses from distal stomas, fistulae, or diarrhoea, as in Crohn's disease, are more likely to give rise to clinically significant hypomagnesaemia. Maintaining the serum Mg in the normal range in such patients is problematic, since Mg salts not very well absorbed and, in high doses, may exacerbate diarrhoea. Nonetheless these may be administered orally in limited doses in the form of magnesium oxide or glycerophosphate and have some benefit. In severe cases as much as 160 mmol of magnesium may need to be administered intravenously over 48 hours to correct the problem. The usual amount given per day in parenteral nutrition is 8-12 mmol MgSO_4 . In patients with recurrent hypomagnesaemia whose nutritional state is reasonable, or who are unsuitable for home parenteral nutrition, we have found (20), as an alternative to weekly visits to the hospital for peripheral intravenous infusions of Mg salts, that self-administered daily or alternate day subcutaneous fluids with Mg are extremely successful and very easy to administer. 0.9% saline (500-2000 ml/day) and/or 5% dextrose (500 ml), containing up to 34 mmol KCl and/or 4 mmol MgSO_4 per litre, may be infused via a fine butterfly needle inserted by the patient or carer into the subcutaneous fat. This proved to have several beneficial effects. Firstly the serum Mg was restored to normal and remained there. Secondly, PTH and serum Ca levels rose. Thirdly, the salt and water counterbalanced the GI fluid losses so that the patients became less thirsty and drank less. This resulted in less flushing of fluid through the GI tract and reduced losses of Na, K, and Mg, thereby undoing a vicious circle.

Although the serum Mg usually reflects the state of Mg stores, it can be unreliable at times. The best measure of repletion is to measure urinary Mg before and after Mg infusion. Repletion is signalled by a rise in urinary Mg levels.

6.2. Phosphate

Phosphate is the most abundant anion in the human body, totalling 1300 g or 33,000 mmol. Most of this is in bone (25,000- 27000 mmol). The rest is distributed in the ICF (5000 mmol), with a small amount in the ECF (12-20 mmol). It plays an important part in many enzyme systems and, of course, in energy transfer as ATP. The kidney filters 150 mmol daily, 120 mmol being reabsorbed. Phosphate excretion is also important in acid-base balance since much hydrogen ion is excreted in this form. Many factors influence phosphate metabolism, although no entirely satisfactory regulatory mechanism has been demonstrated so far. Renal excretion of phosphate rises as plasma concentration increases unless renal failure is present. Indeed, high phosphate levels are one of the many problems in renal failure.

During catabolic illness, phosphate is lost from the cells and excreted by the kidney. Conversely, with the onset of convalescence and anabolism, or with glucose or nutrient administration, there is net cellular uptake of phosphate, which may lead to a dangerously low serum phosphate unless adequate phosphate supplements are given at the same time (see under Refeeding Syndrome). Hypophosphataemia causes muscle weakness, cardiac and respiratory failure, impaired consciousness, and death.

6.3. Calcium

Calcium is the most abundant cation in the body (1300 g or 33,000 mmol), with 99% being in the skeleton with only 1 % being freely exchangeable. The normal plasma concentration is 2.2-2.5 mmol/l, with all except 0.01 mmol/l being bound to protein. With a fall in serum albumin associated with disease, therefore, the measured serum calcium

should be adjusted upwards by 0.02 mmol for every 1 g fall in serum albumin between 40 and 25 g/l.

Calcium plays a vital role in neural conductivity, muscle contraction, hormone secretion, and as a second messenger in many metabolic processes. Falls in free Ca levels are associated with tetany, fits, unconsciousness, and even death. Calcium absorption, excretion, and concentration in plasma are regulated by PTH, calcitonin, and vitamin D. 240 mmol of Ca are filtered daily by the kidney, 238 mmol of which is reabsorbed, and only 2- 10 mmol excreted daily. Vitamin D derived from food or from sunlight on the skin is hydroxylated in the liver and again in the kidney to its active and most potent form 1,25(OH)₂D₃. Renal failure is often associated therefore with vitamin D deficiency, secondary hyperparathyroidism and bone disease, necessitating administration of an analogue of 1,25(OH)₂D₃ in the form of 1- α hydroxy-cholecalciferol 0.25-1mg daily. Bone disease is also a feature of some GI diseases and of long term parenteral nutrition. Adequate supplementation of calcium and vitamin D is therefore a vital part of any long-term nutritional management, particularly in infants, children, and pregnant women.

7. Clinical Importance and Consequences of Errors in Treatment

Fluid and electrolyte prescribing is often left to the most junior and inexperienced doctors on the team and this may often result in errors in prescribing, leading to morbidity and even mortality (1-5, 21). Both underprescription of fluid and electrolytes and overload are detrimental to patient outcome (**Tables 4 and 5**) and every effort should be made to ensure, as far as possible, a state of normal balance.

Table 4

Some clinical features associated with salt and water overload

Peripheral oedema
Gastrointestinal oedema
Pulmonary oedema
Congestive cardiac failure
Hyperchloraemic acidosis
Confusion
Increased intraabdominal pressure
Delayed return of gastrointestinal function to normal (prolonged ileus)
Impaired wound healing, anastomotic oedema and anastomotic dehiscence
Pressure sores
Increased risk of deep vein thrombosis
Delayed mobilisation

Table 5

Clinical features of salt and water depletion. In most cases these are non-specific and can be due to other causes as well.

Reduced ECF and plasma volume leading to reduced tissue perfusion and to organ dysfunction
Dry mouth/reduced saliva/parotitis
Sunken facies
Diminished skin turgor
Postural hypotension
Tachycardia
Reduced stroke volume
Impaired renal perfusion

Increased viscosity of pulmonary mucus leading to mucus plugs and atelectasis
Increased blood viscosity

We (22) and others (23-28) have shown that even as little as a 2.5-3 l salt and water overload in the perioperative period can result in increased complications, delayed return of gastrointestinal function and prolonged hospital stay. Conversely, failure to replace lost fluids adequately also results in poor outcome. A recent meta-analysis has shown that maintaining perioperative patients in a state of "fluid balance" leads to 59% fewer complications and 3.4 days shorter hospital stay when compared with patients who are in a state of either over hydration or underhydration (i.e. fluid imbalance)(28). In fluid and electrolyte therapy, accurate diagnosis, monitoring and prescription combined with a clear understanding of the underlying problem are mandatory to obtain the best results and avoid unnecessary morbidity and mortality.

8. Prescription and Administration

Appropriate fluid and electrolyte prescriptions may be administered orally, enterally, subcutaneously, or intravenously, depending on the clinical situation. Before any prescription is written it is important to ask a number of questions:

- 1) Does the patient need any prescription at all today?
- 2) If so, does the patient need this for (a) resuscitation, (b) replacement of losses, or (c) merely for maintenance?
- 3) What is the patient's current fluid and electrolyte status and what is the best estimate of any current abnormality?
- 4) Which is the simplest, safest, and most effective route of administration?
- 5) What is the most appropriate fluid to use and how is that fluid distributed in the body?

If the patient is eating and drinking, the answer to the first question is usually no. In the case of a post-operative patient, for example, any intravenous fluids should be discontinued as soon as possible. Intravenous fluids are often continued unnecessarily, leading to fluid overload as well as increased risk of cannula-site sepsis.

The second question is crucial. Many patients are fluid overloaded because prescriptions based on resuscitation are continued thoughtlessly when maintenance fluids are all that is required. **Tables 2 and 3** show how low such maintenance requirements are, in fact. For example 1 litre of 0.9% saline contains enough salt to meet 2 days' normal maintenance requirements. On the other hand if the patient has lost 2 litres of gastric juice, which as **Table 5** shows is roughly the equivalent of 0.45% saline, then a knowledge of the content of available solutions will allow the most appropriate prescription to be given to replace these losses. In the event of blood loss from injury or surgery, a resuscitation regimen is appropriate to restore and maintain the circulation. In this situation, the recommendation is to infuse 2 litres of a balanced crystalloid (e.g. Hartmann's solution or Ringer's lactate) rapidly, although colloids or a combination of colloids and crystalloids are a viable alternative (29). Large volumes of 0.9% saline are best avoided because of the risk of producing hyperchloraemic acidosis and its undesirable sequelae (30, 31). Once this has been achieved, the prescriber should revert to a maintenance regimen with accurate replacement of any on-going losses.

A combination of salt containing crystalloid and colloidal solutions are currently used during resuscitation to expand the intravascular volume. The properties of some commonly used crystalloids and colloids are summarised in **Tables 6 and 7** and must be borne in mind before prescribing intravenous fluids.

Table 6
Properties of commonly prescribed crystalloids

	Plasma*	0.9% NaCl	Hartmann's	0.18% NaCl / 4% dextrose	5% dextrose
Na ⁺ (mmol/L)	135-145	154	131	31	0
Cl ⁻ (mmol/L)	95-105	154	111	31	0
[Na ⁺]:[Cl ⁻] ratio	1.28-1.45:1	1:1	1.18:1	1:1	-
K ⁺ (mmol/L)	3.5-5.3	0	5	0	0
HCO ₃ ⁻ (mmol/L)	24-32	0	29	0	0
Ca ²⁺ (mmol/L)	2.2-2.6	0	4	0	0
Glucose (mmol/L)	3.5-5.5	0	0	222.2 (40 g)	277.8 (50 g)
pH	7.35-7.45	5.0-5.5	6.5	4.5	4.0
Osmolality (mOsm/L)	275-295	308	274	286	280

*Normal laboratory range from Queen's Medical Centre, Nottingham

Table 7
Properties of commonly used colloids

Colloid*	Sodium mmol/L	Potassium mmol/L	Chloride mmol/L	Osmolality mOsm/L	Weight average molecular weight (kD)	Plasma volume expansion duration (hrs)
Gelatine 4%	145	0	145	290	30,000	1-2
5% albumin	150	0	150	300	68,000	2-4
20% albumin	-	-	-	-	68,000	2-4
HES 6% 130/0.4	154	0	154	308	130,000	4-8
HES 10% 200/0.5	154	0	154	308	200,000	6-12
HES 6% 450/0.6	154	0	154	308	450,000	24-36

*The properties of available colloids vary according to the manufacturer. Newer preparations are suspended in balanced solutions rather than 0.9% saline and may be more physiological.

The ability of a solution to expand the plasma volume is dependent on its volume of distribution and the metabolic fate of the solute, so that while colloids are mainly distributed in the intravascular compartment, once the dextrose is metabolised, dextrose containing solutions are distributed through the total body water and hence have a limited and transient blood volume expanding capacity (**Fig. 5, Table 8**). Solutions like 5% dextrose and dextrose saline are not meant for resuscitation, but are a means of providing free water when this is appropriate. Excessive use of these solutions can result in hyponatraemia with its associated morbidity and mortality.

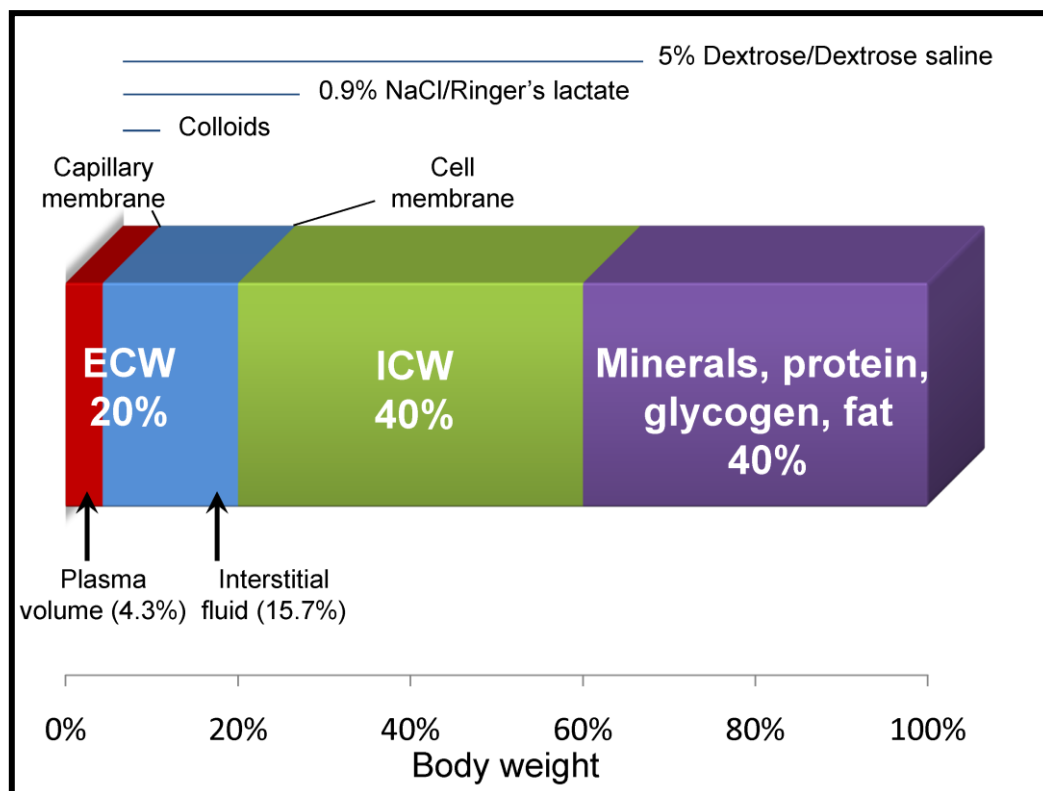


Fig. 5 Distribution of intravenous fluids in the body water compartments

Table 8

Volume of infusion required to expand the plasma volume by 1 L

	Infused volume (mL)	Change in interstitial fluid volume (mL)	Change in intracellular fluid volume (mL)
5% albumin	1000		
25% albumin	250	-750*	
5% dextrose	14000	+3700	+9300
Hartmann's solution or 0.9% saline	4700	+3700	

* Fluid is drawn into the intravascular compartment from the interstitial compartment

Isotonic sodium-containing crystalloids are distributed throughout the whole ECF (including the plasma) and textbook teaching classically suggests that such infusions expand the blood volume by 1/3rd the volume of crystalloid infused (32). In practice, however the efficiency of these solutions to expand the plasma volume is only 20 and 25%, the remainder being sequestered in the interstitial space (33, 34). Although these solutions are used successfully for this purpose the price paid for adequate intravascular filling is overexpansion of the interstitial space and tissue oedema, which has to be excreted once the shock phase is passed. Solutions of dextrose or of hypotonic saline can cause significant hyponatraemia ($\text{Na}^+ < 130 \text{ mmol/L}$) in patients, and care should be taken to avoid this potentially harmful effect, particularly in children and the elderly. Colloids are fluids that contain particles large enough to be retained within the circulation and therefore to exert an oncotic pressure across the capillary membrane (35, 36). Albumin solutions are monodisperse as they contain particles of uniform molecular weight while synthetic colloids contain particles of varying sizes and molecular weights in an attempt to optimise the half life (which is directly proportional to particle size/molecular weight) and plasma volume expanding capacity (which is proportional to the number of particles suspended) of the solutions (35, 37, 38). Although, in theory

colloids that are isooncotic with plasma should expand the blood volume by the volume infused, in practice, the volume expanding capacity of these colloids is only 60-80%. Nevertheless, a given volume of colloid results in greater volume expansion and less interstitial oedema than an equivalent volume of crystalloid. Although, in practice in the UK, we use a combination of crystalloids and colloids for resuscitation, there is, in fact, no firm evidence that the use of colloids rather than crystalloids in the acute phase of injury results in better outcome (39).

8.1. Fluid Therapy

Saline vs. Balanced Fluid Solutions

Fluid prescriptions vary enormously, with some patients receiving as much as 5 litres of fluid, 770 mmol of sodium, and often no potassium at all in a 24 hour period (4).

The normal daily requirements of sodium are in the region of 70 – 100 mmol, but a one litre bag of 0.9% saline contains 154 mmol, and the ability to excrete the excess of sodium and chloride required may be impaired during illness. Furthermore, 0.9% sodium chloride can cause hyperchloraemia due to the high chloride content, leading to reduction in glomerular flow rate and hyperchloraemic acidosis.

Large infusions of saline are associated with acidosis (41) and reduced production of urine compared with balanced solutions such as Hartmann's or Plasma-Lyte 148 (42, 43). A study conducted in healthy volunteers utilising magnetic resonance imaging demonstrated that renal blood flow is decreased following large infusions of 0.9% saline compared with balanced crystalloids. This effect is postulated to be secondary to hyperchloraemia from saline inducing vasoconstriction (44), but also from intracapsular hypertension, resulting in a relative compartment syndrome of the kidney, due to interstitial oedema.

A randomised controlled double-blinded trial comparing 0.9% saline with a balanced crystalloid (Ringer's Lactate (RL)) in patients undergoing abdominal aortic aneurysm repair demonstrated a significantly increased volume of packed red blood cells (780 vs. 560 ml), platelets (392 vs. 223 ml) and bicarbonate therapy (30 vs. 4ml) than those receiving RL. A similar study in patients undergoing renal transplantation demonstrated an increase in metabolic acidosis and hyperkalaemia, a lower urine output and 24h creatinine clearance in those receiving saline compared to those receiving RL (45). An observational study of 3714 patients undergoing abdominal surgery demonstrated an unadjusted in-hospital mortality of 5.6% in those receiving 0.9% saline vs 2.9% receiving balanced crystalloids. Furthermore there were significantly more complications (33.7 vs 23%) in those receiving 0.9% saline (46).

An algorithm for fluid therapy has been proposed in the recently published British Consensus Guidelines on Intravenous Fluid Therapy for Adult Surgical Patients – GIFTASUP (6) and this has been reproduced in Figure 6. In the UK, the National Institute for Health and Care Excellence have published similar guidelines (40), with particular attention to the use of the 5 'R's as an aide-memoire – resuscitation, routine maintenance, replacement, redistribution and reassessment.

Resuscitation: The authors have adapted the following recommendations from the UK Consensus Guidelines (6). The recommendations of this document are shown in *italics*.

Hypovolaemia, due predominantly to blood loss should be treated with either a balanced crystalloid solution (Ringer Lactate or Hartmann's) or a suitable colloid (authors: 'or a combination of the two') until packed red cells are available. Hypovolaemia due to severe inflammation, pancreatitis, or burns should be treated with either a suitable colloid or a balanced crystalloid (or a combination of the two). Care must be taken to administer sufficient balanced crystalloid and colloid to normalise haemodynamic parameters and minimise interstitial overload.

When the diagnosis of hypovolaemia is in doubt and the central venous pressure (CVP) is not raised, the response to a bolus of 200 ml of a suitable colloid or crystalloid should be

tested. The response should be assessed using the patient's cardiac output and stroke volume measured by flow-based technology if available. Alternatively the clinical response may be monitored by measurement of the pulse, capillary refill, CVP, and blood pressure before and 15 minutes after receiving the infusion. This procedure should be repeated until there is no further increase in the clinical parameters.

In severe cases, the need to ensure adequate resuscitation and survival may necessitate paying a price in the form of interstitial salt and water overload (47). It may then take up to 3 weeks for the patient to unload this excess. The important principle is to try and firstly to minimise salt and water overloading, as far as possible, and to recognise when resuscitation is complete and it is appropriate to switch into maintenance mode with a low salt regimen, which allows the patient to achieve a negative salt balance and to excrete the overload.

In high risk surgical patients, preoperative treatment with iv fluid and inotropes should be aimed at achieving predetermined goals for cardiac output and oxygen delivery, as this may improve survival.

Postoperatively, a physiological increase in ADH and aldosterone secretion may occur, leading to a reduction in urine output. A cursory glance, only taking into account the oliguric state, may cause the unscrupulous clinician to prescribe intravenous fluids, despite the absence of other signs of volume deficit. This may cause interstitial oedema, and impair the patient's recovery.

During acute illness, high aldosterone and cortisol levels may cause an increase in urinary losses of potassium, and protein catabolism from cells also cause a net migration of potassium into the extracellular space, increasing intravascular potassium concentrations. If catabolism is extreme, and renal function impaired, a dangerous hyperkalaemia can occur. In the recovery phase of illness, protein anabolism resumes in cells, and potassium is taken back up. This can lead to a hypokalaemia.

In the post-acute phase of trauma or surgical complications, it is sometimes found that, even in the presence of oedema and interstitial fluid overload, the plasma volume is reduced due to serous losses and albumin escape. The renal response to hypovolaemia prevents the excess salt and water being excreted until the plasma volume is expanded. Since artificial colloids contain large amounts of salt, this is one of the few clinical indications for administering salt poor albumin. We find this not only expands the plasma volume efficiently, without adding to the interstitial fluid expansion, but results in a prompt sodium diuresis and hastens the restoration of normal balance (12, 13). There is no case for using albumin for acute resuscitation since it is expensive and no more effective than other colloids or crystalloids.

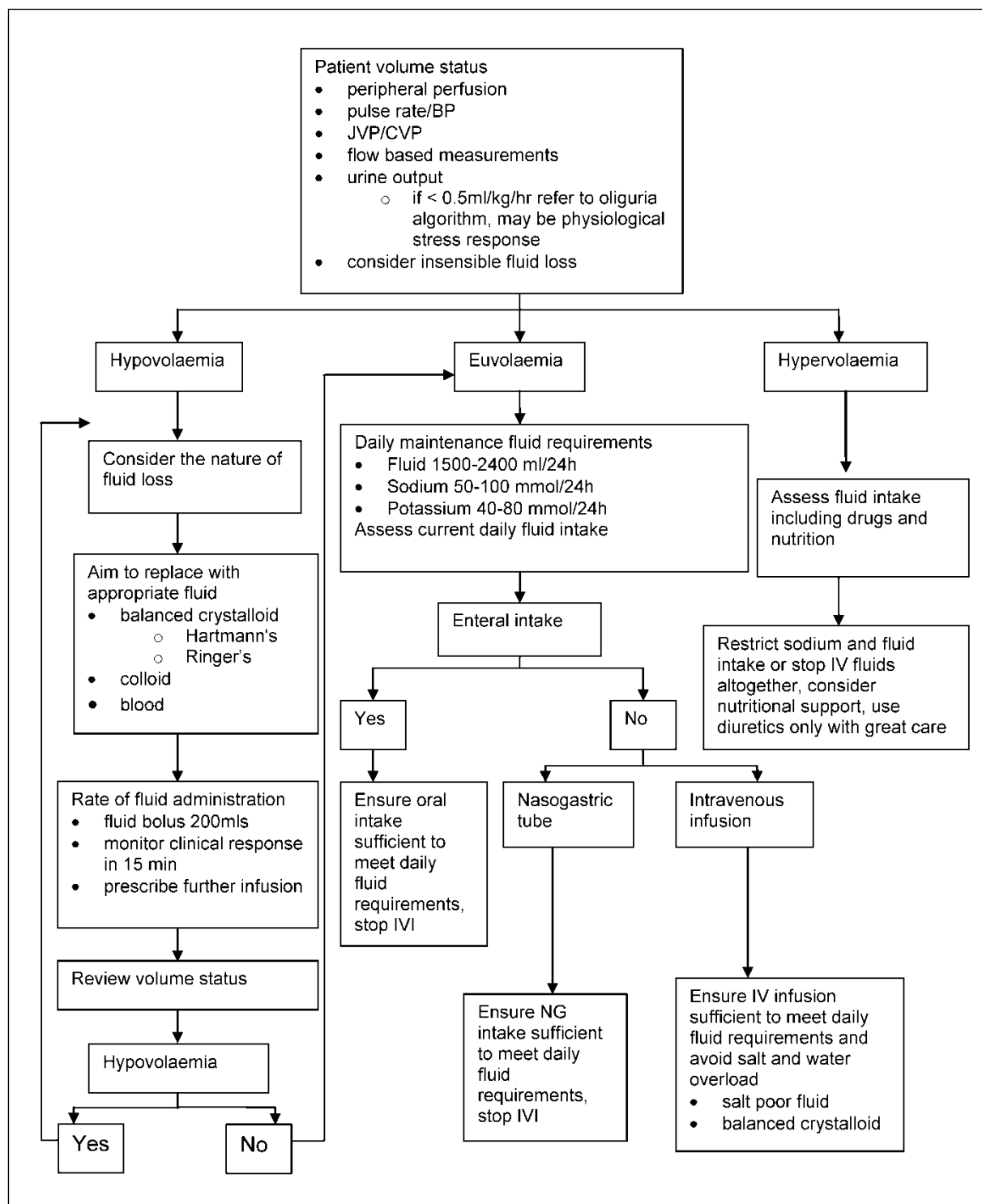


Fig. 6 A suggested algorithm for fluid therapy

Replacement: This may be achieved orally, enterally, subcutaneously, or parenterally depending on the situation.

(a) Oral: one of the commonest causes of morbidity and mortality throughout the world, particularly in children, is diarrhoeal disease. In this as well as in the management of short bowel and inflammatory bowel disease, oral rehydration solutions (see **Table 9**), made locally or prepared commercially, are invaluable. As described above, they are based on the principle that carbohydrate enhances jejunal salt and water absorption. In Asia, satisfactory and cheap solutions have been made from locally available materials i.e. boiled rice water and salt. The WHO formula has a higher salt content than many of

the commercially available preparations available in Europe, which are suitable for less severe cases of infantile diarrhoea (**Table 9**).

Table 9
Oral rehydration solutions

	WHO	Dioralyte (5 sachets in 1 litre)	Electrolade (5 sachets in 1 litre)	Rehydrat (4 sachets in 1 litre)
Na ⁺ (mmol/l)	90	60	50	50
K ⁺ (mmol/l)	20	20	20	20
Cl ⁻ (mmol/l)	80	60	40	50
Bicarbonate (mmol/l)	-	-	30	20
Citrate (mmol/l)	10	10	-	9
Glucose (mmol/l)	110	90	111	91
Sucrose (mmol/l)	-	-	-	94

However, in the management of the salt and water losses caused by short bowel or inflammatory bowel disease, more concentrated solutions can be made by increasing the number of sachets of the commercial powders mixed in each litre of water. It should be remembered that, jejunal salt and water absorption is not only enhanced by the presence of carbohydrate but also by increasing the sodium content of the ingested fluid. Above a concentration of 90 mmol/l of Na in duodenal fluid, there is net absorption, even without glucose. This concentration is, however difficult to tolerate orally. Also, in children especially, it is important to give sufficient water to avoid hypernatraemia.

b) Enteral: Under most circumstances, in hospitalised patients, fluid replacement of moderate or severe losses will be administered intravenously. However there are circumstances where replacement by enteral tube may be appropriate. In short bowel, for example, the slow overnight administration of an enteral feed with fluid and electrolytes allows the reduced absorptive capacity of the bowel to cope, without being overwhelmed. This also encourages the adaptation process.

c) Parenteral: Combining information from fluid balance charts, serial weighing, and serum biochemistry, combined with a knowledge of the likely electrolyte content of any losses (**Table 1**), allows the next day's prescription to be calculated. Monitoring its effects carefully and making adjustments accordingly, allows the continuing and accurate management of even difficult problems.

d) Parenteral nutrition: this being the treatment of GI failure it is common for the patients who require it to have abnormal GI fluid losses e.g. from fistulae, short bowel, Crohn's etc. The challenge, particularly in home based PN, is to replace all losses using the standard all-in-one three litre bags. The net fluid losses can be reduced by (a) keeping oral intake restricted, (b) the use of drugs which reduce gastric acid secretion, (c) the use of octreotide to reduce pancreatic and small bowel secretions, and (d) the judicious use of oral rehydration solutions.

Maintenance: The UK consensus guidelines recommend, particularly in relation to post operative patients, *'To meet maintenance requirements, adult patients should receive daily; Sodium 50-100 mmol, Potassium 40-80 mmol, in water 1.5-2.5 litres by the oral, enteral, or parenteral route (or a combination of routes). Additional amounts should only be given to correct deficit or continuing losses'*. Remember that 1 litre of 0.9% saline contains twice the normal maintenance requirements for Na⁺ and three times the Cl⁻. Also, in critically ill patients, remember to include in the salt and water balance calculations the salt and water given to keep arterial lines open, that used as a vehicle

for giving drugs e.g. antibiotics, and the sodium content of antibiotic compounds and salts.

(a) Oral: The approximate normal oral requirements are also set out in **Tables 1 and 2**, but these may vary according to environmental conditions and circumstances, with variable losses of salt and water from sweat.

Preoperatively, the customary deprivation of food and drink has been shown not only to be unnecessary, but to worsen outcome. A carbohydrate containing drink given 2-3 hours before surgery has beneficial effects (48). Post operatively, oral intake is tolerated much sooner than was thought in the past and before bowel sounds are clinically apparent. Following colonic resection, for example, it can usually be resumed within 24 hours. Nasogastric tube drainage is also overused and trials have shown that, in many cases, they cause more problems than they solve (49). In general, intravenous fluids should be stopped as soon as possible and oral intake resumed. The above measures form part of the modern ERAS (Enhanced Recovery After Surgery) programmes which have done much to improve the results of surgery as well as shortening hospital stay (48, 50).

(b) Enteral: One of the advantages of giving food and/or fluids enterally rather than parenterally is that it is very difficult to overload the patient, since the limit of gastro-intestinal tolerance is reached before any overload is possible. In contrast, there is no limit to the amount that can be given parenterally, and giving excessive amounts of salt and water is only too easy. Nonetheless, the prescriber should be aware of the volume and the electrolyte content of enteral tube feeds. Too aggressive feeding may also provoke diarrhoea and increased GI fluid losses, causing significant fluid deficits.

(c) Subcutaneous(hypodermoclysis). Fluids may be administered via a butterfly needle inserted into the subcutaneous fat of the chest or abdomen (see also under Magnesium). This technique is used commonly in hospitalised elderly or paediatric patients or to deliver fluids in palliative care. Not only can the maintenance requirements of patients be easily met in this way, without recourse to venous cannulation, but, as described above, it can be self-administered effectively by frail patients at home, not only to provide maintenance, but to replace gastro-intestinal fluid and electrolyte losses (20).

(d) Parenteral: this is the technique most fraught with risk, not only because of the mostly avoidable complications of peripheral and central cannulae, but because it is too easy to give excessive amounts. Nonetheless with careful management and prescribing only the maintenance requirements, complications can be reduced to a minimum.

In parenteral nutrition (PN): as much thought should go into the water and electrolyte content of all-in-one feeds as into their nutrient content. Otherwise outcome is adversely affected and PN per se is unjustly blamed for an adverse outcome caused by prescribing errors. In the Veterans Administration trial of post-operative parenteral nutrition versus standard fluids (51), PN was associated with a worse outcome, except in the most malnourished patients (52). Looking critically at this in retrospect and in the light of current knowledge, it seems likely that the two major factors responsible for this outcome were the marked hyperglycaemia and the salt and water overload in the fed group. One of the earliest studies showing adverse outcome associated with salt and water retention was the observational study of Starker et al (53), showing the increased complication rate in patients who gained excess fluid during pre-operative parenteral nutrition. In a controlled study of patients undergoing surgery for GI cancer Sitges-Serra's group (19) compared a fat-based PN formula with a carbohydrate-based PN formula greater degree of salt and water overload associated with the latter.

Nutrition teams are not infrequently asked to administer PN to patients with GI complications in the post acute phase of their illness. These patients tend to have oedema with interstitial fluid overload at the time of referral. It is appropriate, in these cases to give a feed in the lowest possible volume and with little or no sodium, in order to allow a daily negative balance until a normal state is achieved. There seems to be a mistaken idea that some sodium needs to be given daily to every patient, whereas the objective is to restore normal balance with whatever formula is appropriate to that aim.

We have often given a zero sodium feed for up to ten days to such patients until salt and water balance has returned to normal.

Redistribution: Several disease states can cause fluid in the body to redistribute, or accumulate, at the expense of maintaining adequate perfusion to vital organs. In severe sepsis and anaphylactic shock, a marked cardiovascular collapse can occur due to vasodilation of the circulation. The result of this is a drop in the mean arteriolar blood pressure, causing a reduction in end-organ perfusion. In addition, endothelial dysfunction may occur causing an increase in fluid lost into the interstitium. Following major surgery, particularly abdominal, patients may develop gastrointestinal ileus, and sequester several litres of fluid in the gastrointestinal tract, until resolution of ileus occurs.

8.2. Protocols, Guidelines and Training

Every unit should have its guidelines and protocols for fluid and electrolyte management, and all staff should have appropriate training in these. Otherwise erroneous prescribing by inexperienced and poorly trained staff leads to avoidable morbidity and poor outcome.

9. Assessment and Monitoring

When administering fluids to patients, it is important to identify which patients require fluid therapy, based on focussed history taking, performing a directed clinical examination, taking note of the patient's observation, including the fluid input and output charts, interpreting blood results and where appropriate, consideration of the operative theatre notes, particularly the anaesthetic charts.

In addition, the underlying reason for admission needs to be considered, for example in small bowel obstruction or ascites, where litres of intestinal fluid can be sequestered within the gut lumen or peritoneal space.

The main aspects of assessment and monitoring of fluid balance are summarised in **Table 10**.

Table 10
Assessment and monitoring of fluid balance (6)

Parameter	Significance
History	Alerts to likelihood of fluid deficit (e. g. vomiting/diarrhoea/haemorrhage) or excess (e. g. from intraoperative fluids)
Weighing	24-h change in weight (performed under similar conditions) – best measure of change in water balance. Simple to carry out by bedside.
Fluid balance charts	Inherent inaccuracies in measurement and recording. Does not measure insensible loss. Large cumulative error over several days. Good measure of changes in urine output, fistula loss, gastric aspirate, etc.
Urine output	<30 ml/h is commonly used as indication for fluid infusion, but in the absence of other features of intravascular hypovolaemia is usually due to the normal oliguric response to surgery. Urine quality (e. g. urine:plasma urea or osmolality ratio) is just as important, particularly in the complicated patient.
Blood pressure	Cuff measurements may not always correlate with intra-arterial monitoring. Does not necessarily correlate with flow. Affected by drugs, etc. Nonetheless, a fall is compatible with intravascular hypovolaemia, particularly when it correlates with other parameters such as pulse rate, urine output, etc.
Capillary refill	Slow refill compatible with, but not diagnostic of volume deficit. Can be influenced by temperature and peripheral vascular disease.

Autonomic responses	Pallor and sweating, particularly when combined with tachycardia, hypotension and oliguria are suggestive of intravascular volume deficit, but can also be caused by other complications, e.g. pulmonary embolus or myocardial infarction.
Skin turgor	Diminished in salt and water depletion, but also caused by ageing, cold and wasting.
Dry mouth	Usually due to mouth breathing, but compatible with salt and water depletion.
Sunken facies	May be due to starvation or wasting from disease, but compatible with salt and water depletion.
Serum biochemistry	Indicates ratio of electrolytes to water in the extracellular fluid and is a poor indicator of whole body sodium status. Hyponatraemia most commonly caused by water excess. If change in water balance over 24 h is known, then change in serum sodium concentration can guide sodium balance. Hypokalaemia nearly always indicates the need for potassium supplementation. Blood bicarbonate and chloride concentrations measured on point of care blood gas machines are useful in patients with acid-base problems including iatrogenic hyperchloraemia.
Urine biochemistry	Urine sodium concentration may reflect renal perfusion and a low value (< 20 mmol/L) is compatible with renal hypoperfusion, although it is also a feature of the response to injury or sodium depletion. Measurement of urine sodium allows assessment of postoperative sodium mobilisation (see text). Urine potassium measurement is helpful in assessing the cause of refractory hypokalaemia. Urinary urea excretion increases several fold in catabolic states (e.g. sepsis) and is an indication for provision of additional free water to avoid hypernatraemia and uraemia.

9.1. History

The history should be directed to identify recent limited fluid intake, thirst and whether there are any ongoing abnormal losses, for example gastrointestinal fistulae, diarrhoea or vomiting. Note must be paid to the presence of comorbidities and any relevant medications, such as diuretics or antihypertensive agents, which may affect water and electrolyte homeostasis.

9.2. Examination

The clinical examination is an ongoing process, and in acutely unwell patients, may need to be performed several times a day. Physical signs of fluid deficit are indicative but not specific, and no conclusion should be drawn from any single feature. A dry mouth is more often caused by mouth breathing, although it can also be a feature of water or salt and water deficit. Similarly, sunken facies and diminished skin turgor may be caused by salt and water deficit, but are also features of age or major weight loss. The first indication of a falling intravascular volume is a decrease in central venous pressure. With progressive severity, pulse rate increases, followed by a fall in blood pressure with pallor and sweating. The full-blown picture is called 'shock'. In contrast, pink warm peripheries, with rapid capillary refill after pressure, are all suggestive of an adequate circulation. In complex cases or critical illness, such bedside examination needs to be supported by invasive techniques for assessing cardiovascular function.

It should also be remembered that shock due to volume depletion, cardiac causes, or septicemia share many similar features which require expert assessment to distinguish.

9.3. Measurements and Investigations

Urine

As described above, the volume and concentration of urine are important indicators of renal function. Oliguria may be physiological post-operatively, or indicative of intravascular or ECF deficit. If this is accompanied by a concentrated urine and a rising blood urea, it is termed pre-renal failure, correctable by appropriate fluid replacement. A persisting low volume and concentration combined with a rising blood urea and creatinine suggest renal failure due to intrinsic damage, necessitating some form of dialysis. Changes in urine volume must therefore be interpreted in the light of accompanying features and circumstances.

Nurses are often instructed to call junior doctors if the postoperative urine output falls below 30 ml/h. As a consequence, the doctor often prescribes extra saline "just to be on the safe side". This commonly results in salt and water overload. In fact, such "oliguria" is usually a physiological response to surgery. While it is important to identify the patient who has become hypovolaemic and to resuscitate adequately, it is unlikely that a patient who appears well with warm pink peripheries and no tachycardia or tachypnoea has need of volume expansion. Urine output in such patients should be averaged over four hours and interpreted in combination with serial trends in vital signs of circulatory adequacy.

Fluid balance charts

These provide useful information about changes in urine output and abnormal losses e.g. gastric aspirate. With great care in measurement and recording, they may be helpful in assessing balance over 24 hours. However, an assumption has to be made concerning insensible loss, and errors in measurement and recording are common. The cumulative error over several days can therefore be considerable.

Weight

There is no substitute for daily weighing in order to monitor external water balance accurately, yet outside renal units, it is seldom practised. As it is a major safeguard against clinically important errors in fluid volume administration, it is well worth the extra effort and resources required, particularly in complex post-operative cases. It does, of course, only measure external balance, which may conceal significant changes in internal balance between fluid compartments. For example, in the presence of ileus or intestinal obstruction, large volumes of extracellular fluid may be pooled in the gut and therefore be functionally inert. Weight is therefore unchanged despite this clinically important fluid shift, which reduces effective ECF volume and necessitates salt and water replacement. Valuable as weighing is, therefore, it cannot be followed blindly. Like any other parameter, it requires intelligent interpretation in its clinical context and in the light of all the other information available.

Invasive monitoring

Invasive techniques such as insertion of central venous catheters, arterial lines and catheters to measure pulmonary artery wedge pressure are useful to help direct fluid therapy in more complex patients, but are outside the remit of this chapter.

Laboratory tests

Haematocrit

Changes in fluid balance cause increase or decrease in the concentration of red cells e.g., in the acute phase of burn injury, plasma loss may be monitored by frequent haematocrit measurements, which therefore help to guide fluid replacement. Loss of ECF due to gastroenteritis or other causes similarly increases haematocrit. Conversely fluid overload causes dilution.

Albumin

This behaves similarly to the haematocrit in response to fluid deficit or excess. Indeed, dilution by infused crystalloids is one of the main causes of hypoalbuminaemia in surgical patients. Another major cause is the increased albumin escape rate from the circulation in response to inflammatory cytokines.

Urea

The production rate of urea reflects the rate of protein turnover in the body. In catabolic states therefore, the kidney has a greater load to excrete. With renal impairment due to either fluid deficit (pre-renal failure) or intrinsic renal damage, blood urea concentration rises, the rate of increase being greater in the presence of post injury catabolism.

Creatinine

Serum creatinine is a product of muscle metabolism and reflects muscle mass. Normally, therefore, it is higher in a 100 kg muscular man than in a 40 kg elderly woman. For any individual, however, changes in serum creatinine reflect renal function, although this has to fall by more than 50% before the serum creatinine starts to rise. A more sensitive measure of changes in renal function is creatinine clearance.

Sodium

This is expressed as a concentration, i.e. the proportion of sodium to water in the ECF. It is not a measure of the absolute amount of sodium in the body or the need for a higher or lower intake. In fact, the commonest cause of hyponatraemia is dilution by overenthusiastic administration of hypotonic fluids e.g. 5% dextrose. If, however, water balance is known from daily weighing, then changes in plasma sodium can usually be interpreted in terms of sodium balance. For example, if weight is unchanged, a fall in plasma sodium usually implies that sodium balance is negative and that intake should be increased in the next prescription. On the other hand, if weight has increased by 2 kg and the plasma sodium has fallen, the balance of water is positive and hyponatraemia is dilutional. The next prescription should include less water and the same sodium intake as before.

An alternative approach to sodium balance is to measure intake and the sodium content of all fluids lost. This however, is difficult to do accurately as well as being more demanding in staff time and resources.

Patients with high-volume gastrointestinal losses may require measurement of urinary sodium levels. Low urinary sodium levels (<30 mmol/l) may indicate total body sodium depletion, even if plasma sodium levels are normal. Caution must be applied if the patients are taking diuretics, where the urinary sodium values may be misleading.

Potassium

The normal serum potassium lies between 3.5 and 5.3 mmol/l. Levels above 6.0 mmol/l increase the risk of death from cardiac arrest and require urgent treatment which may include extra fluids, intravenous glucose and insulin, bicarbonate, calcium gluconate, intrarectal calcium resonium and even haemofiltration or dialysis. Conversely, concentrations below 3.0 mmol/l indicate the need for potassium supplementation by the oral or intravenous route.

Chloride

Despite the fact that serum chloride measurements do not increase the cost of biochemical screening, the routine reporting of this parameter was abandoned in most hospitals many years ago. However, particularly in patients receiving saline (with its high chloride content in relation to plasma) intravenously, it may be an important parameter to detect the development of hyperchloraemic acidosis in which the plasma chloride is elevated and bicarbonate reduced.

Bicarbonate

Venous or arterial bicarbonate levels indicate acid-base status as described above.

Serial data charts

The sticking of individual reports in the back of notes makes it difficult to detect clinically important trends. The only satisfactory way of monitoring patients with fluid and electrolyte problems is the use of serial data charts on which, each day, important data are recorded, so that changes and trends can be seen at a glance. Our own practice is to record daily weight, serum biochemistry and haematology, etc., on charts which are kept by the patient's bedside. Although transferring data to such charts is time consuming, it reduces time taken in clinical decision making as well as improving the accuracy of prescribing. It also forces one to look at reports and think carefully about their significance.

10. Example to Illustrate the Above Principles

A man aged 60 undergoes left hemicolectomy for cancer of the colon.

Plan: 1) Preoperative: bowel preparation though still used in some units is being increasingly regarded as unnecessary. If used, it involves the loss of 1-2 litres of intestinal fluid which should be replaced with an equivalent volume of Hartmann's solution. Overnight fluid deprivation preoperatively has been found to be unnecessary and counterproductive. A glucose drink, given 2-3 hours before going to theatre is not only cleared from the stomach but improves outcome.

2) Intra-operative: In more complex surgery it is advantageous to control fluid administration using invasive monitoring, but this is unnecessary in a case such as this. The principle is to give enough of the right fluid to replace any losses and to maintain the circulation. Too little or too much have an adverse effect on outcome.

3) Post-operative: In such cases the use of nasogastric drainage tubes is not only unnecessary but potentially harmful. Intravenous fluids should be discontinued within 24 hours, avoiding any salt and water overload, the patient should be given food and drink, and mobilisation begun. This modern approach has been shown to improve outcome. Complications are uncommon but, as in this case, can occur.

Post-operative complications

On the 3rd day post operatively the above patient develops fever, abdominal distension and ileus. An anastomotic leak is diagnosed.

Plan: to drain and defunction the abscess caused by the leak of bowel contents, but first correct fluid imbalance.

1) Gram negative sepsis may cause functional intravascular hypovolaemia (a) through serous leak at the site of the infection, (b) through inflammatory cytokines causing an accelerated albumin escape rate, and (c) through toxic effects causing loss of vascular tone. In addition, there is pooling of extracellular fluid within the bowel due to ileus.

Resuscitation and Replacement should be carried out using a combination of colloid and a balanced electrolyte solution, eg Hartmann's. This should be given until pulse, blood pressure and urine output are restored and further surgery can be safely undertaken.

2) Postoperatively, Nasogastric drainage will probably be necessary because of prolonged ileus. The plan should therefore be to (a) give a **Maintenance** regimen of 2 litres of 0.18% saline in 4% dextrose with 15 mmol KCl per litre to give 2 litres of water, 60mmol Na, 30 mmol K, 90 mmol Cl, (b) **Replace** any gastric aspirate. If, say, this is 2 litres, then we need to give 2 litres of water and (see table) approximately 150 mmol Na, additional Cl⁻ to meet losses of HCl, and 15-30 mmol of K. This can be achieved with 1 litre 0.9% saline, 1 litre 5% dextrose and 15 mmol of KCl in each litre. Monitoring should be carried out, as described above, using weighing, a fluid balance chart, monitoring of vital signs, and daily haematology and biochemistry until normal oral intake is resumed.

11. Summary

Although the principles of fluid and electrolyte balance are relative simple, these are often not well understood, leading to wide variability in prescribing practices and avoidable morbidity and mortality. An understanding of the underlying problem combined

with correct diagnosis, careful monitoring and accurate prescribing are just as important in fluid therapy as they are in any other form of treatment. The effects of disease often mean that the kidneys are unable to compensate for errors in prescribing. The objective of this chapter has been to describe basic principles rather than give dogmatic advice in individual conditions. The intelligent application of such principles will hopefully lead to higher standards of practice.

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