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THE WATER METABOLISM OF THE CAT AND ITS RELATION TO NUTRITION AND HEALTH PROBLEMS

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PREFACE

First of all, I would like to thank my supervisors, Prof. dr. Myriam Hesta and Drs. Norberto Ruiz Suárez, for guiding me through the writing process of this final thesis. I also want to thank my family and friends, for supporting me all these years, and without whom I would not have managed.

CONTENTS

ABSTRACT

In all animal species water is an important component of the body and plays an important role in many physiological processes. Dehydration can affect these physiological functions and overall health. Water balance is regulated by different mechanisms. The most important are the vasopressin feedback loop, the renin-angiotensin-aldosterone system (RAAS) and thirst. The production of highly concentrated urine, the possible preference to receive water from diet, a low thirst drive and an inefficient way of drinking predispose cats for low water intake. Low water intake can lead to feline lower urinary tract disease, which is a common problem in first line practice. In other conditions, an adequate water intake is crucial to control the disease, for example in chronic kidney disease or diabetes insipidus. Yet in other cases, the role of water intake is minor or still uncertain. For example, increased water intake may play a role in the prevention and treatment of obesity.

Many different methods to increase water intake are described. The greatest amount of scientific evidence exists for moist food and dietary sodium, which have been proven to be effective in increasing total water intake in cats. Although dietary sodium might pose some health risks, most studies conclude that this method is safe. Therefore, it is one of the best options for cats and owners that prefer dry food. Nutrient-enriched water supplements also seem to increase water intake, although research regarding this method is limited. Management strategies are highly subject to individual preferences in cats. Water fountains are often recommended, but evidence that they actually increase water intake is lacking. Nonetheless, these methods can make a significant difference in individual cats and are therefore worth trying. More research is necessary to confirm the effectiveness of some other approaches, such as increasing feeding frequency, or to identify new methods.

SAMENVATTING

In alle diersoorten is water een belangrijk onderdeel van het lichaam en speelt het een belangrijke rol in veel fysiologische processen. Dehydratatie kan deze fysiologische functies aantasten en heeft een negatief effect op de algemene gezondheid. Het watermetabolisme wordt door verschillende mechanismen gereguleerd. De belangrijkste zijn het vasopressine-feedbackmechanisme, het renine-angiotensine-aldosteronsysteem (RAAS), en dorst. De productie van sterk geconcentreerde urine, de mogelijke voorkeur om water uit voeding op te nemen, een lage dorstgevoeligheid en een inefficiënte manier van drinken predisponeren de kat voor een lage wateropname. Een lage wateropname kan leiden tot lagere urinewegproblemen (FLUTD), wat een veelvoorkomende aandoening is in de eerstelijnspraktijk. In andere gevallen, zoals chronische nierziekte of diabetes insipidus, is voldoende wateropname essentieel om de ziekte te controleren. Bij sommige aandoeningen is de rol van wateropname gering of nog onduidelijk. Verhoogde wateropname kan bijvoorbeeld een rol spelen in de preventie en behandeling van obesitas.

Er zijn veel verschillende methoden om wateropname in katten te verhogen beschreven. De grootste hoeveelheid wetenschappelijk bewijs bestaat voor natte voeding en toevoeging van zout. Hoewel een hogere hoeveelheid zout mogelijk gezondheidsrisico's inhoudt, concluderen de meeste studies dat deze methode veilig is. Managementstrategieën zijn sterk onderhevig aan individuele voorkeuren van katten. Drinkfonteinen worden vaak aangeraden, maar er is weinig bewijs dat ze werkelijk de wateropname verhogen. Toch kunnen deze methoden een significant verschil maken in individuele katten. Er is meer onderzoek nodig om de werkzaamheid van andere methoden de bevestigen of nog andere mogelijkheden te identificeren.

INTRODUCTION

Water is one of the most important components of the body, comprising about 52% to 67% of the body weight (Zanghi, 2017). Maintaining an adequate hydration status is essential for life, in all animal species, and dehydration can cause a wide range of health problems. Therefore, water homeostasis is closely controlled by the body. In this thesis the main mechanisms that regulate water balance, and their distinct features in cats, will be discussed.

Cats are notorious for drinking very little. The evolutionary origin of the domestic cat may help understand this low thirst drive. Having evolved in desert circumstances, cats are believed to have adapted to a low water intake. Cats have been demonstrated to be able to survive without drinking water on certain diets of fish or meat (Prentiss et al., 1959). The nutrient profile of feral domestic cats consists of 69.5% water (Plantinga et al., 2011; Kremen et al., 2013). However, many pet cats are fed mainly or exclusively a dry diet, which typically contains less than 10% moisture (Laflamme et al., 2008; Gunther et al., 2016; Delgado et al., 2020). This discrepancy may have important consequences for the hydration status and overall health in cats.

Low water intake can lead to feline lower urinary tract disease, which is a common problem in first line practice. In other conditions, an adequate water intake is crucial to control the disease, for example in chronic kidney disease or diabetes insipidus. Yet in other cases, the role of water intake is minor or still uncertain. Since a good hydration status is so important in cats, the question arises as to how we can promote water intake. Numerous different methods are proposed by all kinds of veterinary professionals. For example, a moist diet, a higher dietary salt content, and water fountains are often recommended. Others suggest using water bowls that are wide, shallow, or of a certain material, to have several bowls, or to place them in different locations. These and more potential methods will be discussed, with the objective to identify the most effective and beneficial ones.

The aim of this literature study is to gain knowledge about the causes, consequences, and solutions to inadequate water balance in cats. Understanding this will help cat owners and veterinary professionals to optimize the health and well-being of our feline companions.

1. The water metabolism of the cat

1.1 The importance of water

In all animal species water is an important component of the body. In cats, water comprises between 52% and 67% of the body weight, depending on the amount of body fat (Zanghi, 2017). It is part of bodily fluids like blood, saliva, tears, synovial and cerebrospinal fluid, and it plays an important role in many physiological processes, like thermoregulation, digestion, transport of nutrients, excretion of waste products and toxins, biochemical reactions, and absorbing shocks in joints (Benelam and Wyness, 2010; Jéquier and Constant, 2010). Severe dehydration causes acute and clear clinical signs, such as lethargy, loss of appetite and sunken eyes, and can be fatal. But even mild dehydration can affect physiological functions and overall health, without causing symptoms that are easily noticed by cat owners. For optimal health and well-being in cats, adequate hydration is essential.

1.2 Physiology of water balance

Water is distributed across different compartments in the body. Approximately two thirds of total body water belong to the intracellular fluid compartment. This fluid is located within the cells of the body. The other third belongs to the extracellular fluid compartment, which includes interstitial fluid and plasma. About 2% of total body water makes up the transcellular fluid compartment, and consists of cerebrospinal, gastrointestinal, respiratory, and synovial fluid, among others. Fluids and electrolytes can move from one compartment to another in order to sustain homeostasis (Wellman et al., 2006).

The most important sources for water intake are free water and food. Another part of the water intake comes from metabolic water (Wellman et al., 2006). This is water produced in the body by oxidation of macronutrients, namely fats, carbohydrates, and proteins (Jéquier and Constant, 2010). Water leaves the body through the kidneys (urine), skin (evaporation), respiratory tract and digestive system (feces). Many factors influence the quantity of water loss, such as temperature and humidity of the environment, and physical activity. Cats do not lose a lot of water by sweating, because they only have sweat glands in the food pads. However, they do use saliva as a way of thermoregulation by grooming themselves. Cats also lose significantly less water through respiration than dogs. Dogs can increase their respiratory rate 12 to 20 times when the environmental temperature is 40°C, whereas cats increase their respiratory rate only 4.5 times, showing that in cats, panting in not an effective way to cool down (Wellman et al., 2006).

Since maintaining a good hydration status is so important, the body possesses several physiological mechanisms to preserve water homeostasis. Plasma osmolality, vascular fluid volume, the thirst center, kidneys, pituitary gland, and hypothalamus all play an important part in maintaining water balance (Nelson, 2014).

The main mechanisms that control water balance are the vasopressin feedback loop, the renin-angiotensin-aldosterone system (RAAS) and thirst (figure 1). The first two can limit water excretion, whereas the thirst center can stimulate voluntary water intake (Nelson, 2014).

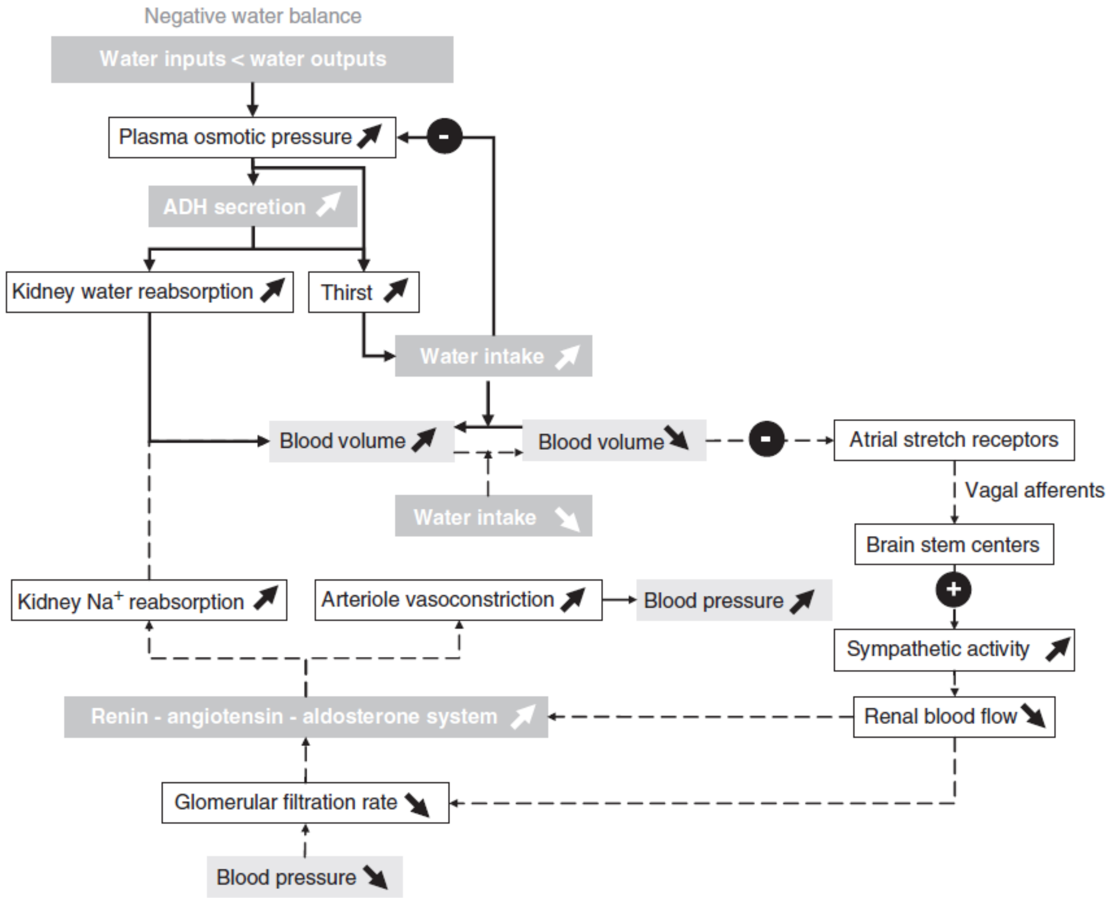

Figure 1: Regulation of water balance. From: Jéquier and Constant (2010).

Vasopressin is part of a hypothalamic-neurohypophyseal-renal axis that works as a feedback mechanism (figure 2) (Knepper et al., 2015). In the case of dehydration, the vascular fluid volume decreases, and, in turn, plasma osmolality rises. This change in osmolality is detected by osmoreceptors in the hypothalamus. As a consequence, vasopressin is released by the pituitary gland. Vasopressin is also known as antidiuretic hormone (ADH) or arginine vasopressin (AVP) and is one of the most important hormones in water balance regulation. It is produced by the hypothalamus and stored in the pituitary gland (Oksche and Rosenthal, 1998; Rossi and Ross, 2008). After its release, vasopressin causes water reabsorption in the kidneys. This leads to a lower urine production and more concentrated urine. Just a 1% increase in osmolality is enough to activate this process (Rossi and Ross, 2008).

When vasopressin binds to V_2 receptors in the kidneys, this causes a cascade of reactions. Eventually, it leads to the insertion of aquaporin channels in the membranes of the collecting ducts, making them more permeable to water (Oksche and Rosenthal, 1998; Rossi and Ross, 2008). These aquaporins play an important role in many water balance disorders, such as diabetes insipidus (Nielsen et al., 2007).

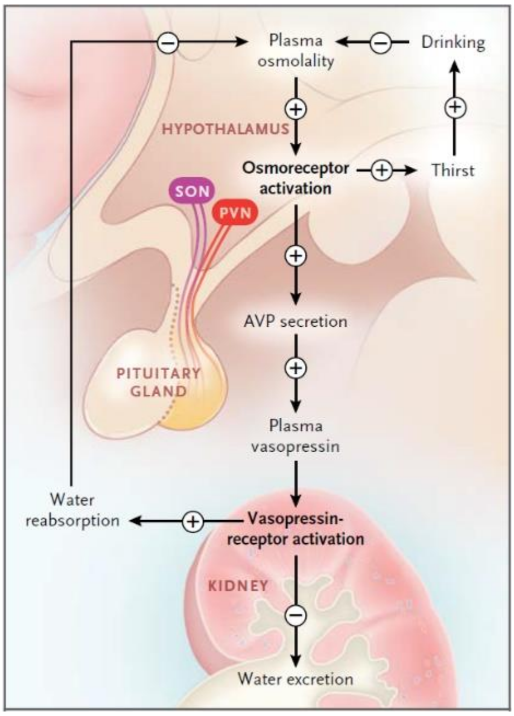

Figure 2: The feedback mechanism of vasopressin. From: Knepper et al. (2015).

The renin-angiotensin-aldosterone system (RAAS) is primarily important for the control of blood pressure, but also for fluid balance. A decrease in both blood pressure and vascular volume lowers glomerular filtration rate, causing the secretion of renin by the kidneys. Renin converts angiotensinogen into angiotensin I, which in turn is converted into angiotensin II by the angiotensin-converting enzyme (ACE). Angiotensin II causes vasoconstriction and sodium reabsorption. Following the concentration gradient of sodium, water is passively absorbed, increasing blood volume and, in turn, blood pressure. Angiotensin II also stimulates the production of aldosterone, which leads to sodium and water reabsorption as well (Fitzsimons, 1998; Syme, 2011).

The sensation of thirst derives from stimulation of the thirst centers in the brain (Thornton, 2010). Thirst is triggered by both the systems discussed above. Apart from vasopressin release, an increase in plasma osmolality causes a sensation of thirst, though at higher osmolality levels (Jéquier and Constant, 2010; Kneppers et al., 2015). Since elevated osmolalities cause water to move from cells to extracellular fluid, this is called cellular dehydration. Angiotensin II, from the RAAS system, is also a thirst stimulus (Blair-West et al., 1994; Fitzsimons, 1998; Thornston, 2010). Angiotensin II is produced in response to a decrease in blood volume. Therefore, this is called extracellular dehydration. The threshold for extracellular dehydration to induce thirst is a lot higher than that of cellular dehydration (Ramsay, 1989; Fitzsimons, 1998). Stimulation of the RAAS system also leads to the release of aldosterone. Aldosterone increases sodium absorption in the kidney, but also stimulates certain brain areas that increase sodium appetite. Intake of sodium will, in turn, make the animal thirsty (Thornton, 2010).

1.3 Characteristic features of water metabolism in cats

The physiological mechanisms that regulate water metabolism have some distinct features in cats. In order to understand these physiological characteristics, it is necessary to have a basic understanding of the evolutionary origin of cats. Domestic cats (*Felis catus)* originate from five different ancestors and were domesticated over 9000 years ago in the Near East, in a region called the Fertile Crescent (Driscoll et al., 2007). They are believed to have evolved from ancestors living in the desert (MacDonald et al., 1984; Zoran, 2002). Due to scarcity of water, these ancestors developed the ability to concentrate their urine considerably (MacDonald et al., 1984; Groves, 2021). This concentrating ability may derive from the long nephrons in the feline kidney (Maurya et al., 2018; Groves, 2021). However, it is also suggested that it has more to do with the nephrons' structural characteristics than with their length (Kriz, 1981).

Dry climate may also have been the reason why cats are designed to get most of their water from their prey (Zoran, 2002). This might explain why many cats generally drink so little. Plantinga et al. (2011) determined the nutrient profile of feral cats of twenty-seven studies in order to establish the profile to which cats may have adapted. According to the authors, feral cats make an appropriate model for the modern domestic cat, since there is little genetic variation between the two. Their study showed that cats are obligatory carnivores and consume mainly small mammals (78%) and birds (16%). The nutrient profile found by the authors consists of 69.5% water. Another study found a similar 67% water in the diet of feral domestic cats (Kremen et al., 2013). Cats have been demonstrated to be able to survive without drinking water on certain diets of fish or meat (Prentiss et al., 1959). In contrast, commercial dry diets contain less than 10% moisture, and therefore do not resemble the water content of the natural diet of cats. This discrepancy may have important consequences for the hydration status and nutrition in cats.

Cats have a relatively low thirst drive and seem to be less sensitive to thirst and dehydration than many other species (MacDonald et al., 1984; Zoran, 2002). As described before, an increase in plasma osmolality leads to an increase in plasma vasopressin and thirst stimulation. In cats, higher plasma osmolality levels are required than in other animals. In humans, for example, the threshold to induce vasopressin release is 280 mosmol/kg (Robertson et al., 1973). In cats, this threshold is 314 mosmol/kg (Reaves et al., 1981). Reaves et al. (1981) suggest that these findings might be explained by the lateral hypothalamus nucleus (NLH), an accessory nucleus of the hypothalamus only found in cats. However, studies to demonstrate this potential correlation have yet to be conducted. Cats also appear to be less responsive to another thirst stimulus, namely angiotensin II. In experiments with intravenous injection of angiotensin II, cats required a significantly higher infusion rate to induce drinking than dogs (Cooling and Day, 1975; Fitzsimons, 1998).

The cat's way of drinking may prove an additional difficulty in water uptake. When animals drink water from a horizontal surface, such as a water bowl or a puddle, they have to work against gravity to move the water up. Some animals, including horses and pigs, use suction to draw water into the mouth. Cats, and most other carnivores, do not have complete cheeks and, therefore, cannot create suction with their mouth. Instead, they have to use their tongue to take in water. Cats do not use their tongue to scoop water, as dogs do. The tongue touches the water surface with its tip curled caudally, adhering water to the dorsal side (figure 3). When the cat draws the tongue back up, a water column is formed and only partially captured in the mouth (Reis et al., 2010). This way of drinking is very inefficient. With each tongue movement only 3/100 of a teaspoon of water is ingested (Groves, 2021).

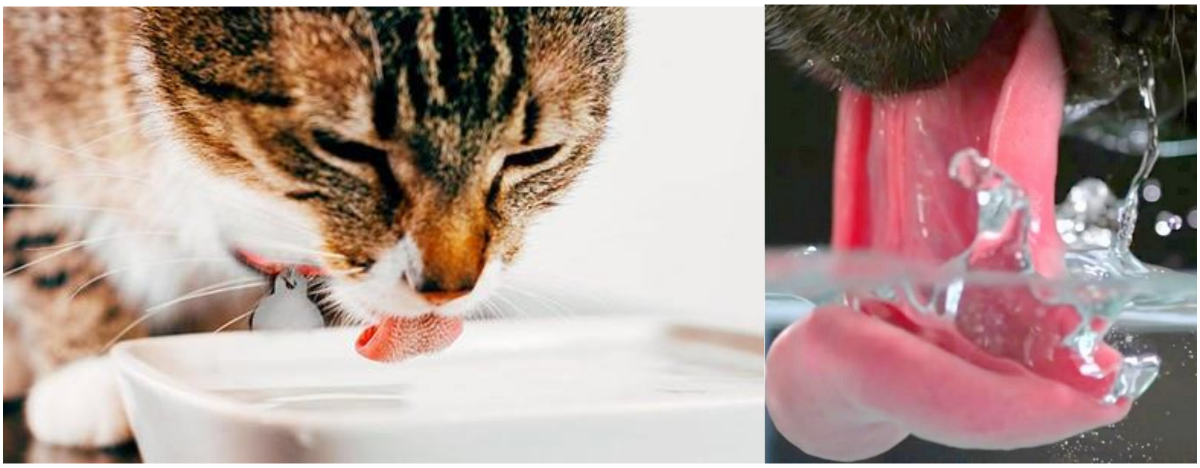

Figure 3: In cats, water adheres to the dorsal side of the tongue (left picture), in contrast to dogs, who scoop water (right picture). From: https://www.purina.com/articles/cat/health/guide-to-cat-hydration and https://www.youtube.com/watch?v=jxQR0zyldYc (last visited 12-08-2021).

The production of highly concentrated urine, the possible preference to receive water from diet, a low thirst drive and an inefficient way of drinking predispose cats for low water intake.

1.4 Water requirements of the cat

There is no consensus as to how much water a cat needs exactly. Water requirement is influenced by many factors, like temperature and humidity of the environment and physical activity (Jéquier and Constant, 2010). Moreover, there are different ways to calculate daily water needs. Three methods that are often used are water:calorie ratio, ml/kcal, and ml/kg of body weight (Zanghi, 2017; Groves, 2021). The National Research Council (NRC) recommends providing 1 ml of water per 1 kcal of food, corresponding to a water:calorie ratio of 1. Other studies found this ratio to be 0.6 to 0.7 in cats receiving a dry diet, and 0.9 in cats given a wet diet (Zanghi, 2017).

Studies that conclusively demonstrate how much water cats need on a daily basis are lacking. Most available sources agree that an adult cat requires approximately 44 to 66 ml/kg/day. Kittens need relatively more water and are recommended to ingest 66 to 88 ml/kg/day (Beaver, 2003; Rossi and Ross, 2008; Pachel and Neilson, 2010). These numbers represent total water need, including drinking water, dietary water, and metabolic water.

2. Health problems related to water metabolism

The water metabolism plays a key role in several health problems. Low water intake can lead to feline lower urinary tract disease, which is a common problem in first line practice. In other conditions, an adequate water intake is crucial to control the disease, for example in chronic kidney disease or diabetes insipidus. Yet in other cases, the role of water intake is minor or still uncertain.

2.1 FLUTD

Feline lower urinary tract disease (FLUTD) is a group of conditions in cats that affect the bladder or urethra. These include cystitis, urolithiasis, and urethral plugs. The most common diagnosis is that of feline idiopathic cystitis (FIC). Cats suffering from FLUTD present clinical signs like dysuria, stranguria, pollakiuria, hematuria and periuria (Forrester and Roudebush, 2007).

Cats that are fed mainly or exclusively dry food have been shown to be at a significantly higher risk of developing FLUTD (Walker et al., 1977; Pusoonthornthum et al., 2012; Tariq et al., 2014). Furthermore, cats suffering from FLUTD showed a significantly lower rate of recurrence of clinical signs when fed a canned rather than a dry acidifying diet (Markwell et al., 1999). Even though there is a correlation between feeding dry food and the occurrence of FLUTD, dry food has not been proven to be a cause of FLUTD (Forrester, 2007). It is a multifactorial disease, and many other causes play a role in developing FLUTD. Stress, middle age, neutering, obesity, inactivity, or sedentary lifestyle and being kept indoors have been found to be risk factors (Jones et al., 1997; Gerber et al., 2005; Forrester, 2007).

2.1.1. Feline idiopathic cystitis

Feline idiopathic cystitis (FIC) is an inflammation of the bladder of unknown origin. So far, a concrete cause has not been identified and diagnosis is based on exclusion (Forrester and Roudebush, 2007). Feeding mainly or exclusively dry food has shown to be a risk factor for developing idiopathic cystitis (Walker et al, 1977; Buffington et al., 1997; Gunn-Moore and Shenoy, 2004; Gerber et al., 2005). However, the significance of water intake in the development of FIC remains uncertain.

Because there is no clear cause of FIC, there is also no specific treatment (Bartges and Kirk, 2006). The goal is to manage the clinical signs. FIC without complications is normally self-limiting and cats recover within 5-10 days without treatment. However, since it causes pain and stress, and predisposes for urethral obstruction and self-traumatization, it is recommended to treat cats suffering from FIC (Gunn-Moore, 2003).

Perhaps the most important recommendation is to increase water intake (Gunn-Moore, 2003; Forrester and Roudebush, 2007). However, it is still unclear whether increased water intake is indeed beneficial in cats with FIC. Diluting urine could reduce the concentration of urea and other harmful substances in the urine (Hostutler et al., 2005; Forrester and Towell, 2015). So far, only feeding moist food versus dry food has been studied. One study showed that cats with FIC showed greater improvement if fed a moist diet, compared to cats fed a dry diet. The urine specific gravity decreased from 1.050 to 1.030 on average when the cats changed from a dry to a canned diet. Also, recurrence of clinical symptoms was significantly lower (Markwell et al., 1999).

A prospective study on how multimodal environmental modification (MEMO) affected lower urinary tract signs in cats with idiopathic cystitis, reported a significant reduction in the frequency of lower urinary tract signs (Buffington et al., 2006). One aspect of MEMO was a diet change to canned food in an attempt to increase water intake. However, many alterations were applied at the same time, making it impossible to determine the importance of each individual factor. Other environmental changes that were made were increased client interaction, conflict resolution in multiple cat households, litter box management, and environmental enrichment, among others. Only fourteen out of 46 cat households followed the recommendation to switch to a canned diet. Therefore, this study is not suitable to draw conclusions about the effect of canned food or water intake on idiopathic cystitis.

Since stress is an important risk factor for the development of FIC, treatment should also include management methods to reduce stress, such as environmental enrichment (Gunn-Moore, 2003; Forrester and Roudebush, 2007). Other treatment options include the use of glycosaminoglycan (GAG) supplements and, if necessary, treating urethral spasms. To date, no other treatments have been proven effective (Gunn-Moore, 2003).

2.1.2. Urolithiasis

Urolithiasis is the formation of calculi, called uroliths or stones, in the urinary tract (Gunn-Moore, 2003; Jones, 2009). It is the second most common cause for FLUTD (Hostutler et al., 2005; Forrester and Roudebush, 2007). There are different types of urolithiasis, depending on the mineral composition of the uroliths. In cats, struvite (magnesium ammonium phosphate) and calcium oxalate (CaOx) are seen most frequently (Gunn-Moore, 2003; Jones, 2009). Non-obstructive urolithiasis causes similar symptoms to other forms of FLUTD. However, there is a risk of obstruction if a urolith becomes stuck in the urethra. This risk is especially high in male cats, since they have a long and narrow urethra. Nonetheless, it is also possible to occur in female cats (Hostutler et al., 2005). Obstructive urolithiasis is life-threatening and should be regarded as an emergency situation. Untreated obstruction can rapidly lead to azotemia, lethargy, bradycardia, tachypnea, and eventually death (Lee and Drobatz, 2003).

Uroliths are formed when there is supersaturation of calculogenic minerals in the urine. Low urine volume, caused by a low water intake or high water loss, enhances mineral concentration. In humans, the prevalence of kidney stones is higher in areas with a hot climate (Borghi et al., 1999). It has also been demonstrated that cats fed a moist diet are less at risk for CaOx urolithiasis than cats fed a dry diet (Lekcharoensuk et al., 2001; Buckley et al., 2011). In one study, thirteen out of seventeen cats with uroliths were fed mainly dry food (Gerber et al., 2005). Feeding a high moisture diet is regarded as one of the most important preventive measures for all urolith types (Lulich et al., 2016).

Therefore, water plays an important role in the prevention of urolithiasis. In human medicine it has been demonstrated many times that high water intake is the best way to prevent nephrolithiasis (Pak et al., 1980; Borghi et al. 1996; Borghi et al., 1999). High water intake will dilute the urine and decrease the concentration of urolith forming minerals. It is recommended to aim for a urine specific gravity of 1.030 or lower (Hostutler et al., 2005; Bartges and Kirk, 2006). In the case of calcium oxalates, not only does dilution of urine lead to a reduced quantity of CaOx crystals, but it also decreases the tendency of crystals to aggregate (Guerra et al., 2005). Furthermore, high water intake will also increase urination frequency, reducing the time that urine spends in the urinary tract. This leads to a reduced chance of crystal growth and urolith formation (Markwell et al., 1998).

Urine dilution affects all urinary parameters that present a risk for urolithiasis, except urine pH (Guerra et al., 2005). Urine pH is important, because different types of uroliths tend to form depending on the acidity of the urine. CaOx uroliths most often occur in urine with an acid pH. Certain breeds seem to be predisposed to CaOx urolith formation, as do cats that are being kept indoors and have an age of 7-10 years. Struvite stones tend to occur in alkaline urine. In contrast to dogs, in cats, struvite uroliths often form in sterile urine (Hostutler et al., 2005).

Decreasing urinary pH by diet has been demonstrated to manage and prevent struvite urolithiasis effectively (Markwell et al., 1998). One study found that there was no significant difference between a canned and dry acidifying diet, and that both proved effective in dissolving struvite bladder stones in cats (Houston et al., 2004). These results suggest that altering the pH of urine may be more important than diluting it. However, since water intake was not measured, it is uncertain whether water intake had an influence on the results of this study. Moreover, decreasing urine pH to prevent struvite stone formation, increases the risk for CaOx urolithiasis. Over the past decades, CaOx urolith incidence has risen above that of struvite uroliths, possibly because of dietary changes made by the pet food industry in an attempt to prevent struvite urolithiasis (Hostutler et al., 2005).

Struvite stones can be dissolved by increasing water intake and decreasing urine pH. Most struvite uroliths are effectively dissolved within 5 weeks and this method excludes anesthetic and surgical risks. Also, it may avoid recurrences induced by suture material (Lulich et al., 2016). CaOx stones will have to be removed by retrograde hydropropulsion and/or surgery (Hostutler et al., 2005). CaOx urolithiasis has a high recurrence rate, which can be effectively prevented with dietary management (Osborne et al., 1991; Hostutler et al., 2005).

2.1.3. Urethral plugs

Urethral plugs are composed of a protein-colloid matrix, consisting of mucoproteins, blood clots or cellular material, and/or crystals, most frequently struvite (Gunn-Moore, 2003; Jones, 2009). The plugs seem to only occur in male cats and can cause urethral obstruction. Increasing water intake, and thereby urine volume, will decrease the concentration of both colloid matrix and crystals, and help prevent the formation of plugs (Bartges and Kirk, 2006). Therefore, it is recommended to promote water intake by feeding moist foods (Gunn-Moore, 2003).

2.2 Chronic kidney disease

Chronic kidney disease (CKD) is very common in cats, especially over the age of ten years (Polzin, 2011; Bartges, 2012; Sparkes et al., 2016). The disease is characterized by an irreversible loss of kidney function, due to functional and structural deterioration (Bartges, 2012). The kidneys play an important role in many physiological processes in the body, including the excretion of waste products, maintaining water balance and blood pressure regulation. These functions are affected when kidney function deteriorates, leading to retention of waste products, and loss of water and protein. In CKD patients, the concentrating capacities of the kidneys are decreased. This leads to polyuria, polydipsia, and a low urine specific gravity (Bartges, 2012). Other abnormalities that may be present are metabolic acidosis, electrolyte imbalances, nonregenerative anemia, systemic hypertension, and hypoalbuminemia, among others. Clinical signs can also include anorexia, weight loss, vomiting, dehydration, ulcerative stomatitis, and gastroenteritis (Plotnick, 2007; Bartges, 2012; Piyarungsri and Pusoonthornthum, 2017).

The exact etiology of CKD is unknown (Sparkes et al., 2016). Chronic low water intake may be an underlying cause of kidney deterioration. In human medicine it has been demonstrated that a high fluid intake is a protective factor against CKD (Strippoli et al. 2011). Interestingly, one study investigating the risk factors for CKD in 130 cats found that dry cat food was associated with a decreased risk of CKD (Piyarungsri and Pusoonthornthum, 2017). In the same study, tap water turned out to increase the risk of CKD, whereas filtered water decreased it. The authors suggest that tap water may contain a high level of fluoride and that this would be the cause of the elevated risk It is also suggested that producing highly concentrated urine may predispose to renal injury (Katz, 2011). More research is necessary to identify the causes of CKD.

Cats suffering from CKD are prone to dehydration, because of polyuria (Polzin, 2011; Bartges, 2012; Polzin, 2013; Sparkes et al., 2016; Piyarungsri and Pusoonthornthum, 2017). An inadequate hydration attributes to the evolution of the disease by deterioration of the kidney function (Plotnick, 2007; Polzin, 2013; Perrier et al., 2014). The polydipsia should compensate for the polyuria. However, it is possible that cats do not drink enough to achieve the necessary compensation (Polzin, 2011; Polzin and Churchill, 2016). Vomiting, a frequent symptom in cats suffering from CKD, also attributes to dehydration.

CKD cannot be cured and treatment focusses on slowing down the progress of the disease and optimizing the quality of life (Bartges, 2012; Polzin, 2013). One of the most important treatment strategies is feeding a renal diet. Renal diets contain a reduced amount of protein, phosphorus and sodium, and often increased vitamin B, potassium, fibers, and energy density (Polzin, 2011). More important, however, is that the animal keeps eating. This is sometimes challenging because cats suffering from CKD can be anorexic and some cats refuse to eat renal diets.

Maintaining a good hydration status is another important aspect of CKD management (Sparkes et al., 2016). Proper hydration aids renal blood flow, appetite, activity, and reduces constipation (Polzin, 2013; Sparkes et al., 2016). To date, there are no studies demonstrating the long-term benefit of hydration management in CKD patients. However, some clinicians see better results with fluid therapy and the consequent diuresis than with the reduction of protein intake (Katz, 2011).

To maintain a good hydration status in CKD patients, subcutaneous fluid therapy is often recommended. Another method that is sometimes suggested is providing water via a feeding tube (Polzin, 2011; Bartges, 2012). However, oral nutritional management is an important and less invasive strategy for long-term hydration maintenance. Unlimited access to clean water is important and feeding a wet diet is recommended (Bartges, 2012; Sparkes et al., 2016).

2.3 Obesity and weight control

Nowadays, obesity is a very common problem in pets (German, 2006; Chandler et al., 2017; Clark and Hoenig, 2021; Shepherd, 2021). The prevalence of obesity in cats has been increasing dramatically. In the USA, the number of overweight cats increased by 90% over a 5-year period from 2007 to 2011 (Chandler et al., 2017). Being overweight negatively impacts life quality and life span. It predisposes for the development of diabetes mellitus, orthopedic problems, FLUTD, dermatologic problems, and neoplasia, among others (Clark and Hoenig, 2021; Shepherd, 2021).

Although caloric restriction and increasing activity are the most important strategies, water may play a role in weight control in cats (Zoran and Rand, 2013; Linder and Parker, 2016). One study showed that cats that were fed a high-water content diet begged less for food, had a lower energy intake and lost more body weight than cats fed a diet with a low water content (Wei et al., 2011). A higher water content increases satiety (Zoran and Rand, 2013). Addition of water enhances the volume of the food. A higher volume activates stretch receptors in the stomach, sending signals to stop energy intake. Water is the most important determinant of energy density because it adds weight to the diet without adding energy. Furthermore, is does not reduce digestibility and has very little effect on palatability (Wei et al., 2011). That is why moist foods can be an effective method to control energy intake.

A study in humans showed that pre-meal water consumption led to a lower subsequent food intake, without affecting the feeling of satiety (Jeong, 2018). Although this has not been tested in cats, it is likely that water intake before a meal would also decrease energy intake in cats. However, it may be difficult to stimulate voluntary water intake in cats, especially at a specific time.

Although most authors conclude that there is no correlation between dry diet and obesity (Buffington, 2008; Beynen, 2015), one study identified a dry diet as major food source as a risk factor for obesity in young cats (Rowe et al., 2015). The authors attribute this to the higher energy density of dry foods. It is also possible that owners easily over-feed with dry food because the portions look small.

Moist diets may be beneficial in the process of losing weight, and possibly also prevent weight gain, by lowering energy density, resulting in relatively large portion sizes, and increasing satiety. More research is necessary to confirm the effects of water intake on weight control.

2.4 Diabetes insipidus

Diabetes insipidus is a rare endocrine disorder characterized by an inadequate production of vasopressin (central diabetes insipidus) or an inadequate response to vasopressin by the kidneys (nephrogenic diabetes insipidus) (Cohen and Post, 2002; Rossi and Ross, 2008). Both forms result in a reduction of the urine specific gravity, polyuria, and polydipsia.

In the case of central diabetes insipidus there is a deficiency of vasopressin, which can be absolute or partial. Most of the time, central diabetes insipidus is idiopathic. Head trauma, neoplasia, cysts, inflammation, and parasite migration, among others, have been recognized as possible causes of central diabetes insipidus in dogs and cats (Nelson, 2014).

Nephrogenic diabetes insipidus (NDI) can be congenital (primary) or acquired (secondary). To date, congenital NDI has not been demonstrated in cats (Nelson, 2014). Acquired NDI can be caused by hypokalemia, hypercalcemia, kidney failure, and ureteral obstruction, among others (Rossi and Ross, 2008).

Polyuria and polydipsia are the dominant clinical signs in animals suffering from diabetes insipidus. Although different treatment options exist, therapy is not strictly necessary as long as the cat has unlimited access to water at all times (Rossi and Ross, 2008; Nelson, 2014).

2.5 Other health problems

Aside from the health problems discussed before, increasing water intake may be beneficial in cats suffering from other conditions that cause water loss, such as diabetes mellitus, hyperthyroidism, vomiting and diarrhea (Robbins et al., 2019; Groves, 2021).

Constipation is another frequent problem in cats (Benjamin and Drobatz, 2020). Especially cats with chronic kidney disease are prone to constipation, because water is absorbed in the colon in the case of dehydration (Quimby, 2016). Older and overweight cats are also at increased risk. Although a dry diet does not seem to predispose cats for constipation, cats suffering from constipation may also benefit from increased water intake and moist diets (Quimby, 2016; Benjamin and Drobatz, 2020).

In humans, dehydration can cause headaches, fatigue, and reduced cognitive function (Kleiner, 1999; Shirreffs et al., 2004; Ritz and Berrut, 2005). Other reported problems in humans are loss of appetite, heat intolerance, light-headedness, a dry mouth, difficulty swallowing and impaired vision (Kleiner, 1999). These issues are difficult to study in cats, but it is likely that cats experience the same complaints in the case of dehydration.

In humans medicine, mild dehydration has also been linked with hypertension, coronary heart disease, stroke, and certain cancer types. However, these are multifactorial conditions and other risk factors will probably have a far greater influence on the development of these diseases (Kleiner, 1999; Benelam and Wyness, 2010).

More research is necessary to fully understand the full range of consequences of inadequate hydration and water balance disorders in cats. It is clear that dehydration has a negative impact on all bodily systems and often causes systemic complaints. Since cats are prone to dehydration, cat owners and veterinary professionals should take extra care to ensure adequate water intake in cats.

3. The role of nutrition: how to increase water intake

Since a good hydration status is so important in cats, the question arises as to how we can promote water intake. Numerous different methods are proposed by all kinds of veterinary professionals. Which of these methods are truly effective and which are most beneficial? In this chapter the most important ones will be discussed. They have been divided into four different sections: methods regarding food, methods regarding free water and other liquids, methods regarding management and non-nutritional methods.

3.1 Methods regarding food

3.1.1 Dietary water: dry versus moist food

According to several studies, feeding moist food to cats results in a higher daily total water intake than feeding dry food (Seefeldt and Chapman, 1979; Kane et al., 1981; Carciofi et al., 2005; Forrester and Roudebush, 2007; Buckley et al., 2011). When cats are fed a dry diet, they actually drink more water than when they are fed a moist diet, but this does not compensate for the lower dietary water intake (Seefeldt and Chapman, 1979; Kane et al., 1981; Carciofi et al., 2005; Forrester and Roudebush, 2007; Buckley et al., 2011). Therefore, the total water intake is higher in cats fed a moist diet, as illustrated by the results of one study in figure 4.

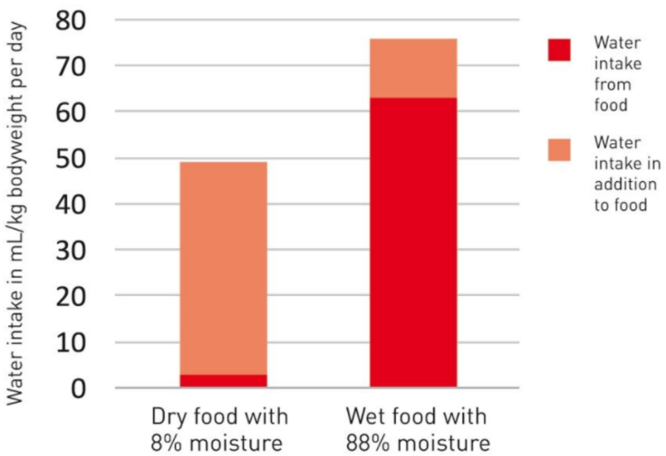

Figure 4: Total water intake is higher in cats fed a moist diet, despite drinking less free water. From: Zentek (1987).

One explanation for this is that food and water intake are interdependent. The animal's energy requirement determines how much an animal will eat, regardless of the type of diet. Wet diets normally have a lower energy density than dry diets. Therefore, cats would eat more of the moist diets and thereby ingest more dietary water (Ramsay and Thrasher, 1991; Handl and Fritz, 2018).

The authors of one study suggested that the fact that cats fed a dry diet have a lower total fluid intake, despite drinking more than cats fed a moist diet, means that cats fed a high moisture diet have a higher total water intake than is physiologically required (Buckley et al., 2011). This suggestion is based this on the assumption that cats adjust their water intake to their physiological needs and that cats fed moist foods take in more water than necessary by meeting their daily energy requirements. In this study, the energy intake was, in fact, the same in all cats, regardless of the diet fed. However, the energy content of the four diets is not mentioned in the article. Furthermore, the authors do not mention what the daily water requirements are, and therefore, if they are indeed exceeded.

Markwell et al. (1999) compared two groups of cats with idiopathic cystitis, fed the dry and canned version, respectively, of the same acidifying diet. In the canned food group, 89% of these cats did not show lower urinary tract signs in the twelve-month period of the study, compared to 61% in the dry diet group. Also, the cats fed the canned version had a significantly lower urine specific gravity, which was also significantly lower than at the beginning of the study two weeks earlier. The cats in this study did not receive medication for their FLUTD signs. Therefore, it was concluded that the results were caused by the diet. However, the results cannot automatically be attributed to the higher water content in these moist foods since there are several other nutritional differences. Most importantly, there is the potential renal solute load (PRSL), which Markwell et al. (1999) define as “the amount of solute derived from the diet that must be excreted in urine”. These solutes include dietary nitrogen, sodium, potassium, chloride, and phosphorus. In this study the effect of the PRSL differences between the dry and moist diet were neglected because they resulted primarily from a greater protein content and were thought to have little influence on urine specific gravity.

In another study Markwell et al. (1998) suggest that, in addition to water content and PRSL, energy content may be responsible for the benefits observed in cats fed a moist diet. The reason for the authors to consider this is the fact that cats will eat more of moist foods with a lower energy content to fulfil their energy requirements, as mentioned above. However, there are no likely explanations as to how energy content would provide health benefits such as a lower urine specific gravity.

The fact that the studied diets contain several nutritional variables, or that certain characteristics of the diets are not mentioned, are recurring problems in studies about moist food in cats. Kane et al. (1981) found that the total water intake was higher when cats were fed a canned diet (78% water) than when fed a dry diet (12% water). Even though water was available at libitum, cats drank no free water at all when fed the canned diet. Two other diets were also compared, but the water content of these diets is unknown. The four diets also differed in other characteristics, such as PRSL, protein content and energy content. Therefore, even though the authors conclude that based on these results cats clearly should be fed a high moisture diet, it is not possible to conclude that the increase in water intake observed was caused by the water content of the diets. In a study conducted by Carciofi et al. (2005) only an 80% moisture diet increased total water intake and urinary water excretion. This diet also caused a lower urinary density. However, again, the four diets used in this study vary in many nutritional characteristics, including water, fat, and protein content, digestibility, and PRSL. Therefore, it is difficult to attribute some of the findings to a specific element.

To determine the effect of water alone, without the possible influence of PRSL and other nutritional differences, Buckley et al. (2011) conducted a study comparing standardized diets that varied only in moisture content. The cats used in the study were given four different diets in successive phases, with water contents of 6,3%, 25,4%, 53,2% and 73,3%, respectively. As expected, free water intake increased as the water content of the diets decreased. The total water intake and average urine volume were only significantly increased for the 73,3% water diet. Furthermore, the specific gravity of the urine and the mean calcium oxalate relative supersaturation were only significantly decreased in this same diet. This study shows that the water content of cat food is an important factor for the urinary parameters and that it is an effective way of increasing total water intake in cats. However, this may be only the case when the moisture content is high enough. A few other studies led to the same conclusion (Seefeldt and Chapman 1979; Carciofi et al., 2005), in which a water-to-dry matter ratio equal to, or higher than 3 was reported. More research is necessary to confirm this hypothesis.

The great majority of studies comparing moist and dry diets in cats show that a moist diet ensures a higher total water intake. According to Gunn-Moore (2004) moist diets are preferred in older cats not only because they provide more water, but also because they are generally less acidifying and contain lower amounts of phosphorus, which is beneficial for kidney health. However, it is possible that a diet must contain a certain amount or fraction of water in order to have an advantageous effect. More research would be useful, and is in fact necessary, to establish such a threshold value of water content.

It is important that cat owners are aware of the benefits of moist diets for cats. It is interesting to take a look at existing data about the feeding practices of cat owners. In a survey with 549 participants in Germany, Austria, and Switzerland, 17% of cat owners responded that they fed only wet food to their cats, 36% fed mainly wet food and a little dry food, 20% fed wet and dry food in equal proportions, 19% mainly dry food and a little wet food and 8% fed only dry food (Figure 5) (Handl and Fritz, 2018). The survey also inquired about health problems and diseases, but no link was found between the type of diet and FLUTD. In this case, clearly most people fed at least partly wet food. This disagrees with the findings of many other studies and surveys, where the majority of cat owners fed exclusively or mainly dry food (Laflamme et al., 2008; Gunther et al., 2016; Delgado et al., 2020). One study concluded that >40% of cat owners in the United States and Australia fed exclusively dry food (Laflamme et al., 2008) and two thirds of the participants of another survey mentioned feeding at least 50% dry food (Delgado et al., 2020). Clearly, there are big differences among studies and the result possibly depend on geographic location, economic situation, or other factors.

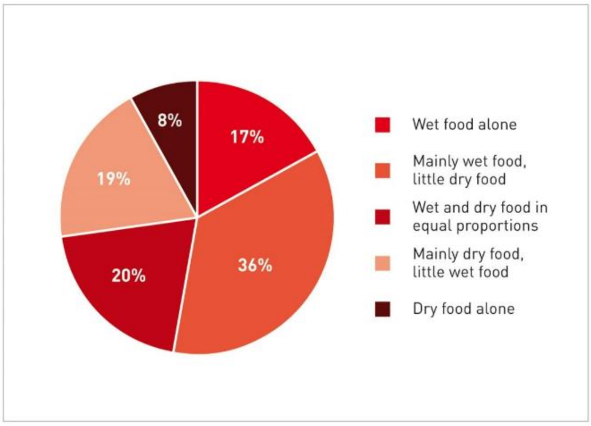

Figure 5: The majority of the cat owners that participated in the survey feed at least partly wet food. From: Handl and Fritz (2018).

If cat owners change their cat's diet to a wet diet, it is important to ensure a good follow-up to ensure that the proposed benefits are indeed achieved. Regular control visits to a veterinary clinic are advised. Moreover, any dietary change should be made gradually (Markwell et al., 1998).

3.1.2 Dietary sodium

Another method to increase water intake in cats that is sometimes recommended is a higher sodium intake. A higher salt content in diet increases water intake by stimulating the thirst drive, via vasopressin and angiotensin release (Thrasher et al., 1980; Blair-West et al., 1994; Hawthorne and Markwell, 2004; Luckschander et al., 2004). Consequently, a higher sodium intake results in a lower urine specific gravity and the production of a higher urine volume and urination frequency (Hawthorne and Markwell, 2004; Luckschander et al., 2004).

Hawthorne and Markwell (2004) found that diets with a high sodium content (11.51–16.74 g Na/MJ or 1.1–1.6 g Na/400 kcal) lead to increased drinking water intake and urine volume, and lower urine specific gravity compared to diets with a low sodium content (<7.32 g Na/MJ or 0.7 g Na/400 kcal). However, no fewer than 23 different diets were compared, divided into two groups (low and high sodium content). The nutritional information of these diets is not mentioned, but it is very likely that they vary in several nutritional factors, making it difficult to attribute the results with certainty to sodium content. Luckschander et al. (2004) compared only two diets, of which macronutrient composition was very similar, resulting in a more reliable comparison. The authors observed a significant increase in water intake and decrease in urine specific gravity when cats were fed a diet with a sodium content of 1,02% (on dry matter basis) compared to a control diet with a 0,46% sodium content. In this study, no significant changes in urine volume were found, which was most likely to be caused by a collection error. The duration of this study was only two weeks. Therefore, no conclusions can be drawn regarding long term effects. In another, 24-month study urine specific gravity was significantly decreased in cats fed a high sodium diet at three months. However, at six, twelve, and 24 months there was no longer a significant decrease (Reynolds et al., 2013). The long-term effects of high-sodium diets are, therefore, still debatable.

Increasing salt content in order to increase water intake is not without risks. Studies focus on three major hazards: hypertension, a negative effect on kidney function, and calcium oxalate urolith formation.

In human medicine, high salt intake has often been associated with a risk of high blood pressure (Intersalt Cooperative Research Group, 1988; Vedovato et al., 2003). This is sometimes extrapolated to other species. If there is indeed a correlation between dietary salt and blood pressure, dietary salt could represent a serious risk. Chronic hypertension can, in turn, lead to other health issues, affecting for example the kidneys, eyes, brain, and heart. Nevertheless, contrary to popular belief, most studies on the topic do not find a negative effect of high salt intake on blood pressure (Buranakarl et al., 2004; Luckschander et al., 2004; Kirk et al., 2006; Xu et al., 2009; Syme, 2011; Reynolds et al., 2013). Reynolds et al. (2013) concluded that a high dietary salt intake (3.1 g/Mcal ME) over the course of 24 months did not affect blood pressure. On the contrary, according to some authors a reduction of sodium could actually activate the renin-angiotensin system and thereby increase blood pressure (Greco et al., 1994; Syme, 2011; Reynolds et al., 2013). An extensive study by Chetboul et al. (2014) studied the effects of sodium intake on cardiovascular values over the course of 24 months. A high-salt diet (1.3% sodium, 2.27% chloride) and a control diet (0.35% sodium, 0.070% chloride) were compared. Except for salt content, the nutritional composition of these diets was similar. The study found no significant effect of dietary salt intake on blood pressure. Not a single cat in the study showed systemic hypertension during the study period. The study also checked heart rate, cardiac morphology, and myocardial function, none of which were affected by dietary salt intake. In human medicine it has been demonstrated that sodium needs and response to dietary sodium vary among individuals. Therefore, it may not be possible to give the same recommendations to everyone (Ely, 1997). The same could be true for cats, although this has not yet been studied. At this moment it remains controversial whether elevated dietary sodium has negative effects on blood pressure.

Due to the potentially negative effects of sodium on the kidneys, sodium restriction is sometimes recommended in cats suffering from chronic kidney disease (CKD). The origin of this recommendation can, again, be found in human medicine. Jones-Burton et al. (2006) concluded that a lower salt consumption might decrease the rate of renal function loss and therefore be beneficial in kidney patients. According to Sanders (2004), dietary sodium is unlikely to pose a risk to healthy individuals, but it probably does to patients suffering from CKD. It is uncertain whether these results can be extrapolated to cats. So far, only one study with cats suggests a harmful effect of dietary sodium on kidney health, observing increased serum concentrations of creatinine, urea, and phosphate (Kirk et al., 2006). However, in other studies these values remained normal (Xu et al., 2009; Reynolds et., 2013). Xu et al. (2009) found that both blood pressure and renal function were not affected by a 1.11% (on dry matter basis) sodium diet, which was compared with a 0,55% sodium diet in a study taking place over the course of six months. In this study healthy cats were used. Therefore, the effects of sodium in cats with underlying diseases remain controversial and should be studied further. Reynolds et al. (2013) concluded that a high dietary salt intake (3.1 g/Mcal ME) over the course of 24 months did not affect renal function. Glomerular filtration rate (GFR) and urinary protein-to-creatinine ratio were not affected by high sodium contents over the course of these two years. Interestingly, according to one study, not a high-salt, but in fact a low-salt diet induced detrimental changes in kidney health, namely a reduced glomerular filtration rate (GFR) and kaliuresis. Supplementation of NaCl suppressed the renin-angiotensin-aldosterone system without increasing blood pressure. This could be beneficial for kidney function and might even slow the progression of CKD (Buranakarl et al., 2004). Likewise, Hughes et al. (2002) identified sodium as one of the factors that decreased the odds of chronic renal failure in cats, together with dietary fiber, magnesium, and protein. Since these nutrients were studied together, the isolated effect of sodium in uncertain. To date, the link between dietary sodium and kidney function in cats is insufficiently studied to draw conclusions.

The third proposed risk of an increased dietary sodium content is that of calcium oxalate urolith formation. Some studies showed that urinary calcium excretion was significantly higher in cats that were fed a high sodium diet, compared with cats fed a low sodium diet (Devois et al., 2000; Kirk et al., 2006). On the contrary, other studies found that cats fed a high sodium diet had a significantly lower urinary calcium oxalate relative supersaturation (CaOx RSS), suggesting a reduced risk of calcium oxalate urolithiasis (Lekcharoensuk et al., 2001; Stevenson et al., 2003; Hawthorne and Markwell, 2004)**.** Hawthorne and Markwell (2004) found that a sodium content of 11.51 to 16.74 g Na/MJ (1.1 to 1.6 g Na/400kcal) did not lead to higher calcium concentrations in the urine, while it did have the benefits of promoting water intake, urine volume and decreasing urine specific gravity. Lekcharoensuk et al. (2001) found an odds ratio of 0.48 (half as likely) to develop calcium oxalate uroliths in cats that were fed a high sodium diet compared to a low sodium diet. These studies show that also in the case of calcium oxalate urolithiasis, the effects of dietary sodium are controversial. Again, more research is necessary to provide clarity on the topic.

Studying dietary sodium in feline nutrition presents a number of complications. A frequently recurring problem is that there are no clear definitions of ‘high’ and ‘low’ sodium levels in pet foods (Nguyen et al., 2017). Another difficulty is the variety of units of measurement being used in these studies, making it difficult to compare them. Dietary sodium was expressed in percentage on dry matter basis, in grams per Mcal, in milligrams per MJ, among others. Yet another complication is that some studies speak of 'sodium' and others of 'salt' (sodium chloride).

Dietary sodium turns out to be an effective way to increase water intake. The next questions that arise are which amount of sodium would be the most beneficial and if there is a maximum limit above which health risks are too great. The difficulties mentioned above make it challenging to establish such values. The maximum limit value that is mentioned most often is the one established by the National Research Council (NRC), namely 1.5% sodium on dry matter basis (Xu et al., 2009). According to the NRC cats can probably tolerate very high levels of sodium as long as drinking water is available ad libitum (Chandler, 2008; Reynolds et al., 2013). Nguyen et al. (2017) suggest that the safe upper limit of dietary sodium is 740 mg/MJ metabolizable energy. According to the American Association of Feed Control Officials (AAFCO) establishing a maximum concentration of dietary sodium is not useful, since an excess of sodium would decrease the palatability and, as a result, consumption of the diet, before it would lead to negative health effects (AAFCO, 2013).

Given that sodium increases water intake in cats, one might ask whether it is more or less effective than feeding moist food. So far, no studies have compared these two methods in cats. Stevenson et al. (2003) compared the effect of dietary moisture versus dietary sodium on urine composition in dogs. Dogs that were fed a diet containing 0.30 g Na/100kcal drank significantly more water than when fed a diet containing 0.05 g Na/100kcal. However, no significant differences were found in urine specific gravity and urine volume. Therefore, if these results can be extrapolated to cats, dietary sodium would not be of great benefit in cats with FLUTD, despite the increased water intake. However, as mentioned above, Hawthorne and Markwell (2004) found that dietary sodium did increase urine volume in cats. In accordance with what was demonstrated in cats, in the study by Stevenson et al., dogs drank significantly more water when fed a 7% moisture diet compared with a 73% moisture diet, but total water intake was significantly higher in the latter. Additionally, the 73% moisture diet led to significantly lower urine specific gravity, which was not the case for the higher sodium diet. This suggests that dietary moisture has more benefits than dietary sodium, especially in the case of FLUTD. However, the urine specific gravity differences were only significant in miniature Schnauzers and not in Labrador retrievers, which means that there are breed differences. It is also unclear if these results can be extrapolated to cats. Therefore, even though the study has interesting results, it does not provide useful information for cats.

Increased dietary sodium seems a promising method to enhance water intake in cats. The majority of data show no adverse effects of dietary sodium on health parameters. At this moment, however, there is still no unambiguous consensus regarding any of the possible risks of high dietary sodium levels. Therefore, it may not be the preferable method to increase water intake. Especially in cats suffering from FLUTD, CKD, or other health problems, other methods may be safer. More research is necessary to evaluate the dangers of dietary salt augmentation. If this method would prove to be safe, it could be of great benefit, for example when cats or their owners show a preference for dry food instead of moist food. If a high sodium diet is given, it is recommended to monitor kidney function and blood pressure (Forrester and Roudeboush, 2007; Xu et al., 2009). Also, fresh drinking water must always be available.

3.1.3 Dietary protein

In various studies higher dietary protein levels seem to increase water intake and urine volume in cats (Hashimoto et al., 1995; Zentek and Schulz, 2004; Meconça et al., 2018). Urine volume increases due to osmotic diuresis following the higher excretion of urea. In the study of Medonça et al. (2018) cats that were fed diets containing 499.0 and 505.0 g/kg crude protein (on dry matter basis) drank 73% and 50% more water, respectively, than cats fed a diet containing 248.0 g/kg crude protein. However, the diets differed in crude protein level as well as in sodium, starch, and other nutrient content, which also may have influenced the results. This problem is also seen in another study where total water intake was 1.3 times higher for a 64% crude protein diet compared to a 28% crude protein diet (Garcia et al., 2020). Drinking water intake increased 1.4 times and urine volume was 1.7 times higher. However, since protein and sodium levels both varied it is impossible to say if the higher intake was caused by either one separately. As discussed before, sodium levels also increase water intake in cats. Zentek and Schulz (2004) documented a significant difference in total water consumption and urinary water excretion between high and low protein diets. Although most other nutrients did not show great differences, sodium levels showed, again, variety. This makes it impossible to draw conclusions about the effect of protein alone. One study concluded that a higher dietary protein content does not lead to a higher water intake. Urine volume did increase, but not significantly (Funaba et al., 2003).

There are no studies that can clearly attribute an effect on water intake to protein content specifically. Higher levels of dietary protein may have a positive effect on water intake in cats. However, a high protein content may also play a role in the progression of chronic kidney disease. More research is necessary to determine the effect of dietary protein on total water intake in cats and the potential risks of this method.

3.2 Methods regarding free water and other liquids

3.2.1 Nutrient-enriched water

Another possible method to increase water intake in cats is the use of nutrient-enriched water, which was studied by Zanghi et al. (2018a). The water contained amino acids, glycerol, and electrolytes, among other nutrients. The sodium content of the water was low. Cats that had access to nutrient-enriched water drank significantly more water during the study, showing an increase of 60%, and had a significantly higher urine output. Furthermore, they had a significantly lower specific gravity, which was maintained during the full two months study period. In cats that only had access to tap water, urine concentrations of phosphate, urea nitrogen and creatinine had lowered significantly after one week of nutrient-enriched water treatment. When cats had access to both nutrient-enriched water and tap water they showed preference for the nutrient-enriched water. An interesting and important observation in this study was that the individual reaction of the cats to the nutrient-enriched water showed a lot of variation.

The results of this study suggest that the increased consumption of nutrient-enriched water was caused by a preference for this water and not by thirst. When cats have access to only tap water, the thirst drive appears to be weak, even when the urine osmolality is high. The nutrient-enriched water used in this study contained many different components and the separate effect of each is unknown.

The authors suspect whey protein, glycerol, and poultry flavor to be the cause of the increased intake. It would be useful to examine the effects of these components separately in other studies.

In addition to this study, Zanghi et al. (2018b) investigated the effects of nutrient-enriched water with and without poultry flavor. Cats drank significantly more of both versions of the nutrient-enriched water compared with tap water. These results indicate that addition of whey protein and glycerol to water increases the total water intake in cats. However, the increase was greatest in the nutrient-enriched water with added poultry flavor.

Wils-Plotz et al. (2019) studied two nutrient-enriched water supplements that only varied in gum content (0.11% and 1.1%) and compared them to tap water. No significant difference was found for the two supplements. They both proved to increase total water intake and urine volume and to decrease urine specific gravity, urine osmolality, and urine protein and creatinine values.

Providing nutrient-enriched water could be useful for cats that are fed a dry diet. For example, cats that show a preference to dry food, need a specific diet that is only available in a dry form, or when the owner prefers to give dry food. In these cases, nutrient-enriched water could be a solution with fewer risks than a high sodium diet. It could also be used in addition to other methods. Since the reaction of cats to nutrient-enriched water varies among individuals (Zanghi et al., 2018a), some cats may receive more benefits from this method than others.

3.2.2 Purified water

Wooding and Mills (2007) investigated a possible preference in cats for purified water compared to chlorinated tap water. Provided with the two types of water, the cats drank significantly more from the tap water. These results might be explained by the fact that the cats are used to tap water. The duration of this study was only 48 hours. Therefore, it is unknown whether cats might get accustomed to purified water over time. Similar results were found in a survey held among 549 cat owners in Germany, Austria, and Switzerland (Handl and Fritz, 2018), in which cats preferred tap water over filtered tap water or still mineral water.

3.2.3 Milk

Many cats like to drink milk, but it is often strongly advised against. Milk can be harmful to cats because it contains lactose, and some cats are lactose-intolerant (Craig, 2019). Kittens produce the enzyme lactase, but this decreases in the weaning period. Most adult cats no longer produce lactase and are therefore unable to digest lactose. Consumption of large amounts of milk will cause diarrhea, which in turn can cause dehydration. According to Beynen (2017), amounts of up to 6 grams of lactose per day, corresponding with 130 ml of cow milk, will not cause diarrhea in an average cat. However, the author recommends 85 ml as the maximum amount. Royal Canin mentions 2 g/kg bodyweight as the maximum of lactose that should be ingested, the equivalent of 200-250 ml of milk (Handl and Fritz, 2018).

To avoid lactose-induced problems, special ‘cat-milk’, which is lactose-free, has been created. However, it is unlikely to contribute to an improved water balance. These products are often rich in fats so that amounts that would be necessary to promote fluid intake will be predisposing for weight gain and obesity.

3.2.4 Miscellaneous

Some authors suggest chicken or meat stock, or fish water, such as tuna juice, as ways to promote water intake in older cats (Gunn-Moore, 2004; Acierno, 2017). Gunn-Moore warns that stock should not contain onion or onion powder, because of the risk of hemolytic anemia. However, there is no evidence that shows that these products actually increase water intake.

3.3 Methods regarding management

3.3.1 Water fountains

Cat owners often observe a preference for flowing water sources, like running tap water, in their cats. Consequently, there are numerous water fountains for cats on the market, promising to increase water intake. They are also often recommended by veterinarians. However, not many studies have been conducted to test the effectiveness of these water fountains.

One study found that cats drank slightly more from a flowing water fountain than a still water fountain, but the difference was not significant. Moreover, there was a great individual variation in daily water intake in the cats. Some cats drank significantly more water from the flowing water fountain, others from the still water source. Yet other cats showed no great differences in water intake (Pachel and Neilson, 2010). Therefore, whether cats prefer a still or flowing water source may be an individual factor. Grant (2010) comes to the same conclusion. In this study most cats drank slightly more from a water fountain than from a bowl, but again not significantly. One cat responded to the fountain with barbering and vomiting and refused to drink from the fountain. Urine osmolality did not differ significantly between the two groups. The author suggests that the observed increase in water intake from fountains may be caused by cats playing with the fountain, thereby spilling water, and creating falsely increased water intake. Forty-two percent of the cat owners stated that their cats played with the fountain. This makes it difficult to interpret the results. Both studies were conducted with a small number of cats (nine and thirteen respectively) and over a limited time span. It may be possible that cats grow accustomed to water fountains after a longer period of time and will then make more use of it. Studies with a larger number of cats and a longer study period would be useful to better study the correlation between water fountains and water intake in cats.

One study did examine still, circulating, and free-falling water bowls, leading to the conclusion that bowl type did not influence water intake in cats (Robbins et al., 2019). The only urinary parameter that was significantly different was the urinary osmolality, which was higher for a circulating bowl. Three cats showed an individual preference for one of the bowl types, each one for a different type. In a survey conducted by Handl and Fritz (2018) the majority of cat owners mentioned that when cats were provided water both in a bowl and a fountain, they showed a preference for the bowl. However, no statistical conclusion could be drawn from the results.

Despite the fact that water fountains are often recommended, there seems to be a lack of scientific evidence about water fountains increasing water intake in cats. However, studies show that cats have strong individual preferences when it comes to water source. Therefore, it might be worth trying this method in cats that need a higher water intake. Furthermore, water fountains may serve a purpose as environmental enrichment. In the study of Grant (2010), 83% of the cat owners believed their cats liked the fountain. As 42% of the owners reported that their cats played with the fountain, it might promote a more active lifestyle.

<u>3.3.2 Characteristics of water bowls and location of water sources</u>

Advices regarding the characteristics and placement of water bowls are often given by veterinary practitioners, handbooks, websites, and researchers. However, for many of these advices there is no or little scientific evidence, since not many studies have been performed investigating them.

Several characteristics of the water bowl, such as depth, width, and material, may play a role in a cat's water intake. In a survey conducted by Handl and Fritz (2018) cats preferred bowls with a diameter of less than 15 mm compared to larger bowls. The authors suggest that the reason for this is that cats may use their whiskers to locate the edges of the bowl and water surface. On the other hand, it is often said that cats would prefer wide bowls, because they would not like their whiskers to touch the edges. There is no scientific evidence that confirms either hypothesis.

In the survey, most people offered water in ceramic bowl. Other materials that were used were plastic, metal, and glass. The survey revealed no general preferences. Half of the cats had access to only one water point and in 41% of the cases the water bowl was placed next to the food bowl. Cats seemed to prefer water bowls that were located in another room than the food bowls. Many cat owners also reported that their cats drank from watering cans, flowerpots, ponds, puddles, and other water sources. Cats might prefer to drink outdoors, and outdoor cats were found to use a larger amount of water points. Even though the survey provides a lot of interesting information, it does not serve as scientific evidence for many of the observations. Unfortunately, no useful studies exist on this topic.

Despite the lack of evidence, it is to be recommended to try several management methods, by way of trial and error, because cats show many individual preferences in food and water intake. In any case, it is advisable to offer water in a variety of bowls, differing in size and material, in different places, and to always offer fresh water.

<u>3.3.3 Adding water to food</u>

Another possibility to enhance water intake is to add water to the normal diet. Carciofi et al. (2005) tested the influence of adding 50% water to a dry diet. This did not result in an increase of total water intake or urine excretion. No other studies explored this possibility. As mentioned earlier, several studies demonstrated that a dietary moisture content of 80% or 73,3%, or water-to-dry matter ratio of at least 3, respectively, have shown to increase total water intake (Seefeldt and Chapman, 1979; Carciofi et al., 2005; Buckley et al., 2011). If enough water is added to the diet to reach these moisture levels, this method may be beneficial. However, some cats may not like the taste or texture of food soaked in water. Depending on individual preference, adding water may or may not lead to higher water intake.

<u>3.3.4 Feeding frequency</u>

One study found that cats drink more water if they are fed multiple times a day (Kirschvink et al., 2005). The authors tested two diets, varying in energy content, feeding one, two, and three times a day. The water intake was significantly higher each time for both diets. This suggests that increasing feeding frequency can help promote water intake in cats. More research is necessary to confirm this.

Finco et al. (1986) studied the difference in water intake between periodic and continuous feeding and found that cats drank less water when fed periodically. However, this periodic feeding entailed access to food for only one hour daily, between 11 am and 12 am, whereas the other group had access to food the entire day. It would be useful to know if intermittent access to food over the day also influences water intake in cats. Even though ad libitum access to food seems to increase water intake, it can also lead to overeating and obesity. Therefore, it may not be a favorable method to enhance water intake in cats.

3.4 Non-nutritional: subcutaneous and intravenous fluid therapy

Subcutaneous fluid administration is often mentioned as a way to prevent dehydration in cats suffering from CKD (Sparkes et al., 2016; Acierno, 2017). Some cat owners may be able to perform this procedure at home. Especially in advanced stages of CKD this may be helpful. However, there is no strong evidence supporting this. There is also a risk of inducing hypertension due to high amounts of sodium chloride in parenteral fluids (Roudeboush et al., 2009). Sparkes et al. (2016) prefer offering water via a feeding tube over subcutaneous administration, because it is a more physiological method.

Intravenous fluid therapy is an effective and fast method to stabilize dehydration in a clinical setting, but it cannot be done by owners at home. It is an invasive method with risk of infection and fluid overload. Also, many cats find a trip to a veterinary clinic stressful. Therefore, this should not be considered as a way to ensure adequate hydration on a regular basis.

3.5 Conclusion

The most important methods to increase water intake have been discussed above. Some have proven to be effective, for others evidence is lacking. Many studies have been conducted regarding dietary water (moist versus dry foods) and dietary sodium. For these two methods there seems to be the most evidence that it can increase water intake in cats and be of benefit in certain health issues. As we have seen, dietary sodium poses several potential risks. However, most studies concerning these risks, do not confirm them. With the current knowledge, feeding a moist diet seems to be the number one choice to increase water intake. However, some cats or their owners prefer dry food. In this case, a dry diet with a high sodium content may present an effective alternative. Another option is to supplement a regular dry diet with nutrient-enriched water. This has shown to be a promising approach to increasing water intake and may entail fewer risks than increasing dietary sodium. The water-enhancing effect of these three methods seems to be the least affected by individual preference.

All options regarding management (water fountains, characteristics, and location of water bowls, adding water to food and feeding frequency) have not been studied enough to be proven effective. On top of that, they are very subject to individual preferences of cats. This does not mean they cannot make a significant difference in water intake in individual cats. In fact, it would be advisable for cat owners to try these methods on their cats.

Some other methods also lack scientific support. Dietary protein, purified water, milk and, most importantly, the much-recommended water fountains have not been demonstrated to be effective. More research is necessary to gain knowledge about these methods.

Whichever method is used, it is to be recommended that they are introduced gradually to the cat. Sudden changes in diet can cause food aversion and gastrointestinal problems. Also, it may take time to get used to new elements, such as water fountains or new water bowls. Cats should always be monitored and have regular health checks by a veterinary practitioner.

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