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The Effect of Marathon Cycling on Renal Function

Abstract

The stress of strenuous long-term exercise may alter renal function. Whether this is also true for marathon cycling is unknown so far. The purpose of this study was to evaluate renal function following competitive marathon cycling. We investigated 38-male, well-trained recreational cyclists credibly not taking any kind of doping who participated in the Ötztal Radmarathon. Blood and urine specimens were taken the day before, immediately after and one day after competition.

Baseline renal functional parameters - normal before competition - increased significantly afterwards and remained elevated during 24 hours of recovery. The rises in serum creatinine, urea and uric acid were 20, 54 and 42 % ($p < 0.001$ respectively). The corresponding decline in estimated creatinine clearance was 18 %. In all athletes the serum urea/creatinine ratio rose above 40, fractional sodium excretion and fractional uric acid excretion fell below 0.4 % and 15 %, indicating reduced renal perfusion. The observed effects lasted for at least 24 h despite a stable fluid balance during the race and an expanding plasma volume (PV) in the recovery period. Levels of haematocrit remained unchanged immediately post-race but significantly declined from 0.44 to 0.41 on the following day ($p < 0.001$). The calculated rise in PV was + 10.8 %. Electrolyte homeostasis was preserved throughout the observation period. Post-exercise proteinuria was small and of the mixed glomerular-tubular type. There was neither evidence for exercise-induced haemolysis, nor for significant skeletal muscle damage.

The finding obtained from well-hydrated recreational athletes reveals that the extraordinary strains of marathon cycling influence renal function only on a minimal scale. Though minor, the physiological effects were long-lasting. The results obtained suggest that a reduced renal perfusion is the mechanism responsible for the slight impairment of renal function following exhaustive marathon cycling.

Key words
Renal hypoperfusion · endurance exercise · plasma volume expansion

Introduction

Strenuous marathon running has demonstrated to alter renal function exacerbated by thermal stress under hot and humid conditions [9,17]. During prolonged exercise extensive fluid losses through sweat and respiration may lead to systemic dehydration and hypovolemia accompanied by an exercise-induced impairment of renal blood flow and function [4,25,30]. Numerous studies have assessed renal function in the field of marathon running and cross-country skiing [7,8,11 – 13,17,25,26,30]. So far, however, none has focused on the renal impacts of competitive marathon cycling.

Exercise-induced impairment of renal function ranges from the asymptomatic transitory increase of renal functional parameters to the severe complication of acute renal failure [11,13,17,25,26].

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Accepted after revision: July 15, 2002

Bibliography
Int J Sports Med 2003; 24: 131–137 © Georg Thieme Verlag Stuttgart · New York · ISSN 0172-4622

A few cases of renal failure requiring dialysis occurred after marathon running [5,13,15]. They were considered to be the result of renal hypoperfusion aggravated by haemolysis and rhabdomyolysis due to considerable amount of sports-specific, eccentric loads of running [20]. Cycling, however, mainly comprises concentric strains with negligible eccentric parts which generally do not cause any significant skeletal muscle damage [33]. According to our knowledge, until now no case of cycling-associated acute renal failure has been reported most probably due to the differing sports-specific muscular strains of cycling.

The objective of the present study was to investigate renal function in strenuous marathon cycling. We studied a group of healthy male, and well-trained athletes participating in the Ötztal Radmarathon 1999, a very challenging one-day cycling race in the Alps of the Tyrol, with respect to their renal function, volume status and electrolyte balance.

Material and Methods

Subjects

Thirty-eight male volunteers out of 1420 participants of the Ötztal Radmarathon held on August 29th, 1999 in the Tyrol, Austria, were subjects of the study. All study participants were experienced amateur cyclists and well-prepared for the race. To the best of our knowledge they did not use any kind of doping. The athletes were considered to be healthy according to case history and prior clinical and laboratory examinations. The subjects provided written informed consent in accordance with the guidelines established by the Institutional Ethics Committee. Before competition they were instructed to maintain an adequate fluid intake *ad libitum* being rich in carbohydrates. After the race they recorded the amounts of fluid replacement. The athletes were weighed three times on electronic scales (Tefal®): immediately before and after the race as well as 24 hours before and after.

Characteristics of the race

The Ötztal Radmarathon is a 1-day cycling race with an extraordinary workload. The race is held every year in the Alps of the Tyrol. Its total distance is 230 km at an altitude of 550 – 2500 m above sea level. The total altitude difference is 5500 m, including 4 mountain passes: Brennerpaß (1374 m), Jaufenpaß (2097 m), Timmelsjoch (2509 m) and Kühtai (2097 m). Its course profile is comparable to that of the hardest mountain stages of professional cycling. The race took place under dry and fine weather conditions. During the race temperatures ranged from 14 – 21 °C, and humidity from 55 – 85 %.

Blood and urine analysis

Blood and urine specimens were taken the day before, immediately after and one day after competition. The blood samples were obtained by venopuncture of a cubital vein. The venopuncture was done in lying position at the same time in the morning of the day before and after the race. On the day of competition it was performed in the afternoon immediately after the individual finish. They were placed on ice and analyzed for the various parameters on the same day whereas the urine specimens collected at the same time were stored frozen until analysis. Haematocrit (Hct), haemoglobin (Hb) and red blood cell (RBC) count were measured in an automated cell counter (Coulter Gene S analyzer). Plasma and urinary concentrations of sodium (Na^+), potassium (K^+) and chloride (Cl^-) were determined by ion-sensitive electrodes (Hitachi analyzer 717 and 911; Roche Diagnostics, Basel, Switzerland), the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) by photometry on the same analyzers. The plasma and urine osmolarities were measured by using the freezing point depression method (FISKE® 2400 osmometer, FISKE® Associates, Massachusetts, USA). Creatinine was assessed by the Jaffee reaction, serum protein by the Biuret method and the activity of creatine kinase (CK) colorimetrically by using the standard method of the "Deutsche Gesellschaft für Klinische Chemie". C-reactive protein (CRP) in plasma and albumin urine were determined by an immunoturbidimetric assay (Tina-quant®, Roche Diagnostics, Basel, Switzerland; reference range < 0.7 mg/dl), and β-2-Microglobulin by means of a microparticle enzyme-immunoassay method on an AxSYM analyzer (Abbott Diagnostika, Wiesbaden, Germany). Proteinuria was characterized by performing SDS gel electrophoresis with Phast System™ (Amersham Pharmacia, Uppsala, Sweden). The concentrations of all other parameters measured were assessed by standard methods.

Formulas

Fractional sodium excretion ($FENa^+$) was calculated according to the formula [28]:

$$FE\ Na^+ = Na^+_{(urine)} \times creatinine_{(serum)} / Na^+_{(serum)} \times creatinine_{(urine)}.$$

Fractional excretion of uric acid (FEUA) was determined accordingly.

Transtubular potassium gradient (TTKG) was calculated according to the formula [32]:

$$TTKG = K^+_{(urine)} \times osmolarity_{(serum)} / K^+_{(serum)} \times osmolarity_{(urine)}.$$

Percentage change in plasma volume (%ΔPV) was calculated from pre- and post-exercise levels of Hct and Hb according to the equation by Strauss [29]:

$$\%\Delta PV = 100 \times (Hb_{pre}/Hb_{post}) \times (1 - Hct_{post}/1 - Hct_{pre}) - 100.$$

Creatinine Clearance (CCr) was calculated according to the formula by Cockroft and Gault [9]:

$$CCr\ (mL/min) = (140 - age) \times lean\ body\ weight\ [kg] / creatinine_{(serum)}\ [mg/dL] \times 72.$$

Statistical analysis

The changes in the various biochemical markers over the observation period were calculated by the Kruskal-Wallis test followed by the Dunn's Multiple Comparison test. Correlations between the markers and the athletes' baseline characteristics were computed by simple linear regression analysis using the SPSS software package, version 9.0 (Chicago, Illinois, USA). Statistical significance was assumed at a level of $p < 0.05$.

Table **1** Baseline characteristics and race results of the athletes

	Mean value	*SD*	*Range*
Age (yr)	35	7	24–52
Height (cm)	179.6	7.1	164 – 199
Body mass (kg)	74.0	7.1	60.9 – 88.6
BMI (kg/m^2)	22.9	1.8	19.86 – 28.63
Training km (in 1999)	6350	3265	1500 – 15 000
Race time (h/min)	9 h 38 min	49 min	8 h 06 min – 11 h 03 min
Average speed (km/h)	22.5	1.3	26.9 – 20.8
Total placement			24–629
Weight loss (kg) [%] *(immediately after race)*	–1.72 [–2.3]	1.49	–5.1– + 1.0
Weight loss (kg) [%] *(24 hours after race)*	–0.73 [–1.0]	0.94	–3.6– + 0.6
Fluid substitution (L)	5.1	1.4	2.5 – 7.3

SD = standard deviation, BMI = body mass index

Results

Baseline characteristics

All athletes finished the marathon successfully and without any symptoms. Most of them were able to fulfill their personal expectations. The average race time was 9 h 38 min, the mean amount of fluid substitution during the race was 5.1 L, and the immediate weight loss was 1.7 kg. During the following 24 hours the athletes regained about 1 kg. Their baseline characteristics and race results are summarized in Table **1**.

Renal functional parameters

Serum creatinine, urea and uric acid increased significantly during the marathon and remained elevated for the following 24 hours (Fig. **1**). The levels of urea and uric acid rose by 54 and 42 %, respectively. In all athletes the urea/creatinine ratio increased to values greater than 40 indicating prerenal azotemia. The ratio remained elevated above 40 in 34 athletes (89 %) even 24 hours after the race. The mean increase of creatinine by 20 % post-race corresponds to a decline in CCr of 18 % according to the formula of Cockroft and Gault (Table **2**). No correlations were found between the rises in serum creatinine or urea and CK or LDH immediately after the race (for creatinine versus CK: r = 0.067, p = 0.7; versus LDH: r = 0.126, p = 0.47; for urea versus CK: r = –0.033, p = 0.85; versus LDH: r = 0.000, p = 1) with no significant changes 24 hours afterwards.

Proteinuria: Eleven athletes (31 %) showed proteinuria >15 mg/dl immediately after the race reaching values between 50 – 500 mg/dl. Of these athletes 8 showed albuminuria, 1 selective glomerular, 1 tubular and 1 mixed glomerular-tubular proteinuria. In 3 athletes albuminuria persisted for at least 24 hours. Urine concentrations of β-2-microglobulin were hardly detectable pre-race and did not change post-race either (Table **3**).

Volume status

The changes in Hct, Hb, RBC count and protein showed a significant direct correlation over the entire observation period. Representative of these parameter changes the courses of Hct and Hb are illustrated in Fig. **2**. Immediately after the race the mean Hct value remained unchanged but significantly dropped in all

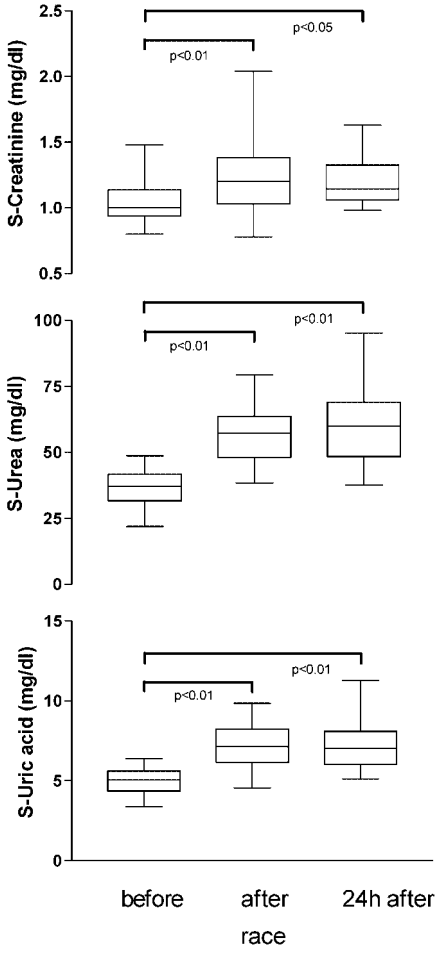

Fig. **1** The course of serum creatinine, urea and uric acid during and after the marathon.

cyclists on the following day (p < 0.001). Consequently, the calculated %ΔPV remained unchanged during the race but increased between 2 and 36 % on the following day (%ΔPV$_{median}$ = + 10.8 %). Both parameters, Hct and %ΔPV, indicate pronounced PV expansion. Laboratory markers (e.g. LDH) indicating exercise-induced haemolysis remained negative during all the time. There was a significant correlation between the changes in Hct and total body weight losses (r = 0.451; p = 0.006) immediately post-exercise. No correlations were found between the changes in Hct and racing time, age, training status (i.e. training km in 1999) or the

Table **2** Changes in serum parameters over the observation period presented as median values and interquartile range (IQR)

	before race	*immediately after*	*24 h after*
Creatinine (0.7 – 1.4 mg/L)	1.00	1.20**	1.15*
IQR	0.94 – 1.13	1.03 – 1.37	1.07 – 1.27
CCR (mL/min) ‡	106	87**	88**
IQR	91 – 122	74 – 104	84 – 98
Urea (10 – 50 mg/dL)	37	57**	60**
IQR	32 – 42	49 – 63	52 – 69
Uric acid (2.4 – 7.5 mg/dL)	5.0	7.1**	7.0**
IQR	4.4 – 5.6	6.2 – 8.2	6.2 – 8.0
Na^+ (135 – 152 mmol/L)	145	145^{NS}	141^{NS}
IQR	143 – 146	145 – 146	141 – 142
K^+ (3.4 – 4.6 mmol/L)	3.8	4.2**	3.9^{NS}
IQR	3.7 – 4.0	4.0 – 4.4	3.8 – 4.1
Cl^- (95 – 110 mmol/L)	102	99^{NS}	99^{NS}
IQR	100 – 103	98 – 102	100 – 103
Ca^{2+} (2.1 – 2.7 mmol/L)	2.29	2.52*	2.25^{NS}
IQR	2.25 – 2.36	2.44 – 2.57	2.21 – 2.30
Mg^{2+} (0.6–0.95 mmol/L)	0.83	0.92^{NS}	0.86^{NS}
IQR	0.79 – 0.88	0.84 – 0.97	0.83 – 0.87
Hct (0.4 – 0.52)	0.44	0.44^{NS}	0.41**
IQR	0.42 – 0.46	0.43 – 0.45	0.39 – 0.43
Hb (13.3 – 17.7 g/dL)	14.9	15.1^{NS}	13.9**
IQR	13.4 – 16.4	13.8 – 16.6	12.7 – 15.3
%ΔPV‡		-2.2^{NS}	$+ 10.8^{\dagger}$
IQR		–4.6-+ 2.1	10.2 – 18.1
Osmolarity (mosmol/L)	300	305^{NS}	297^{NS}
IQR	297 – 302	301 – 308	294 – 300
Protein (6.3 – 8.2 g/dL)	8.05	8.08^{NS}	7.27**
IQR	7.74 – 8.32	7.73 – 8.36	7.16 – 7.54
LDH (120 – 240 U/L)	169	217^{NS}	209^{NS}
IQR	156 – 190	203 – 244	191 – 234
CK (12 – 126 U/L)	63	119**	234**
IQR	45 – 90	92 – 192	110 – 278
CRP (<0.70 mg/dl)*	all < 0.70	all < 0.70	1.49**
IQR			0.87–1.95

*p < 0.05, **p < 0.01 (Dunn's Multiple Comparison test), † p < 0.001 (one sample t test).
^{NS} = non significant; ‡ calculated parameters.

amount of fluid substitution. The decrease observed in protein was 8% 24 hours after the race. Compared to the protein decline the increase in %ΔPV of 10.8% was more pronounced indicating a protein influx into the intravascular compartment. The results of all serum parameters investigated and calculated (i.e. CCr and %ΔPV) are shown in Table **2**.

Electrolyte status

Serum electrolytes: Immediately after the race increases in serum electrolytes were observed for K^+, Ca^{2+} and Mg^{2+} by about 10%. There was no marked change in Na^+ and Cl^-. Na^+ was observed to fall insignificantly whereas Cl^- remained unchanged until 24 hours after the race. K^+ and Ca^{2+} returned to baseline values whereas Mg^{2+} remained elevated by about 5%.

Urine electrolytes: Urine osmolarities were already rather high pre-exercise, and did not substantially change post-exercise (Table **3**). $FENa^+$ showed an immediate decrease of about 50% immediately after and a further decline on the following day corresponding to a pre-race value of about 30%. A comparable pattern could be observed for FEUA. TTKG doubled after the race and returned to the baseline value within the next day. The courses of $FENa^+$, TTKG and FEUA are illustrated in Fig. **3**.

Discussion

Our study demonstrates minimally altered renal function in well-hydrated athletes involved in strenuous marathon cycling. In the absence of systemic dehydration and significant skeletal muscle injury an exercise-induced reduction of renal blood flow (RBF) is the most likely mechanism underlying this decrease in estimated CCr. The finding supports previous studies suggesting a stress-induced sympathetic overdrive to be responsible for reduced renal function after exhausting exercise [16, 30].

Table **3** Changes in urine parameters over the observation period presented as median values and interquartile range (IQR)

	before race	*immediately after*	*24 h after*
Osmolarity (mosmol/L)	879	762^{NS}	981^{NS}
IQR	613 – 1007	635 – 885	814 – 1057
Na^+ (mmol/L)	166	78**	44**
IQR	137 – 180	62 – 100	19 – 73
K^+ (mmol/L)	79	144**	69^{NS}
IQR	42 – 95	107 – 161	56 – 97
Cl^- (mmol/L)	136	106*	78 **
IQR	33 – 160	23 – 160	26 – 160
Protein (mg/dL)	6.5	12**	9^{NS}
IQR	3 – 10	7 – 17	6 – 15
Protein/creatinine (mg/g)	46	72**	54^{NS}
IQR	30 – 61	50 – 102	44 – 62
Albumin (mg/dL)	0.8	1.8**	0.9^{NS}
IQR	0.7 – 1.1	1.0 – 3.8	0.8 – 2.3
Albumin/creatinine (mg/g)	6.9	13.3**	5.9^{NS}
IQR	4.5 – 12	7.3 – 23.7	4.3 – 12.2
β-2-Microglobulin (mg/L)	0.05	0.03^{NS}	0.05^{NS}
IQR	0.02 – 0.09	0.01 – 0.1	0.01 – 0.07

*p < 0.05 ; **p < 0.01 (Dunn's Multiple Comparison test), ^{NS} = non significant.

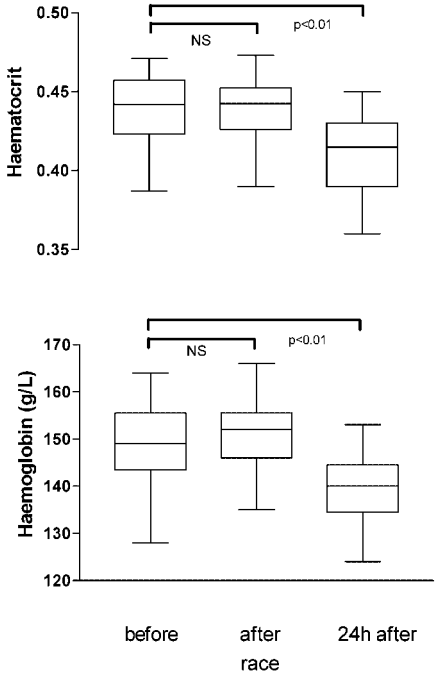

Fig. **2** The course of serum haematocrit and haemoglobin during and after the marathon.

The experience gained in the field of professional multi-stage cycling suggets strenuous long-term cycling to be safe and not at all "nephrotoxic". Nevertheless, respective scientific knowledge is sparse about man's renal function under the stress of long-term cycling. The effects of physical exercise on renal function vary considerably as they depend on several factors. Exercises differing in mode and duration lead to different - sometimes even opposite - impacts on volume status and renal function in differing study populations of amateurs and professionals under changing climatic and environmental conditions. For all these reasons both improved and altered renal functions have been reported [3,13,26,30,31].

The objective of the present paper was to study man's renal function under the stress of marathon cycling in a homogeneous group of recreational athletes. The results obtained consist in minimally altered renal function, enhanced PV expansion, well-preserved electrolyte homeostasis and mild proteinuria. Sufficient fluid substitution is virtually crucial for a successful performance of long-term exercise. The athletes investigated were aware of this circumstance due to their experience and the pre-race information given by us. Their average rate of fluid substitution during the race was 5.1 L, i.e. about 500 mL per hour which is less than the American College of Sports Medicine proposes (≥1000 ml/h). Nevertheless significant systemic dehydration did not occur in the athletes investigated obvious by very moderate weight losses (1.7 kg) and several laboratory parameters. Constant levels of Hct (see Fig. **2**), plasma protein and calculated %ΔPV immediately post-race provide biochemical evidence of a stable fluid balance during the marathon and prove the rate of fluid substituted to have been adequate. Significantly decreasing Hct and plasma protein as well as increasing %ΔPV observed on the following day demonstrate furthermore marked PV expansion during the recovery period [18]. Further volume regulatory responses post-exercise - secondary to an activated renin-angiotension-aldosterone (RAAS) and ADH system - consist in: a) enhanced retention of Na^+ and free water - obvious by sustained elevated urine osmolarities, b) considerably decreasing $FENa^+$, c) a trend to slightly rising Na^+_{serum} and d) marked increases in K^+_{serum} and TTKG [25,26]. These effects were preserved for at least 24 hours. The persistence of impacts may be referred to the prolonged phase of recovery following such extraordinary, exhausting long-term efforts. In this context, however, the finding of rather high pre-race urinary osmolarities requires some explanation. The most likely one is that the study participants were not experienced enough to realize optimal pre-hydration and that the concentrated urines pre-race were the result of some fluid deficit acquired in the very last training days. The

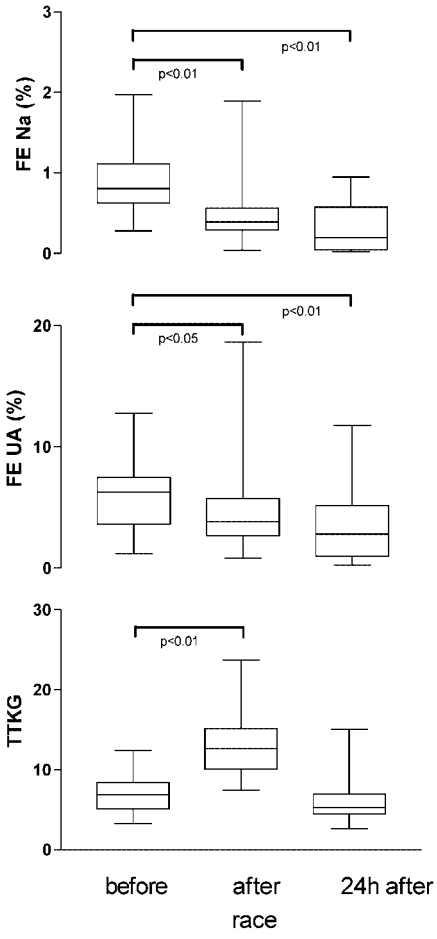

Fig. **3** The course of $FENa^+$, FEUA and TTKG during and after the marathon.

somewhat more diluted urines post-race, however, give proof more likely of sufficient fluid substitution during the race than of potential renal concentration defects as observed in marathon runners [26].

Despite preserved fluid balance we found signs of reduced renal perfusion post-exercise consisting in decreased $FENa^+$ and FEUA, markedly increased serum concentrations of urea and uric acid, and increased serum urea/creatinine ratios >40. The post-race increase in serum creatinine corresponded to a decline in estimated CCr of 18%. However, in the absence of 24h-clearance measurements the question rises whether the increases in creatinine could also have other causes than a decline in renal function. One possibility is an intensified creatinine production rate through catabolic metabolites of muscle damage. But this is rather unlikely for our study population for the following two reasons: first, skeletal muscle trauma was negligible obvious by very slight post-race increases of CK [2]; and second, in a regression analysis no correlation could be found between the post-race concentrations of serum creatinine and CK or LDH. In general, creatinine production decreases with long-term exercise as studies on ultramarathon running with distances of 100–1600 km have shown [7,8]. In contrast, the post-race increases of serum urea and uric acid may theoretically be attributed to a small extent to an enhanced protein catabolism occurring during long-term exercise when the glycogen depots become depleted [10,14]. Nevertheless, this influence of protein catabolism should be minor as major glycogen depletion appears unlikely due to the moderate decline in heart rate response (about 10% observed during the race) and the high degree of individual satisfaction post-race [19]. Moreover the athletes, experienced in marathon cycling, had been explicitly instructed before the race to maintain adequate fluid substitution being rich in carbohydrates.

The mechanism underlying the observed decline in renal function is most likely an exercise-induced reduction in RBF due to a stress-induced overdrive of the sympathetic nervous system through long-term exertion [1,21,30]. This assumption is also based on the finding of Suzuki et al. who measured RBF following exhausting cycling by radionuclide angiography and investigated its relationship to the neurohumoral response during the exercise [30]. They demonstrated a post-exercise reduction in RBF of 53% and a strong corresponding correlation towards the decline in measured CCr and the increase in plasma catecholamines and angiotensin II. Consequently they concluded that an exercise-induced impairment of renal function is caused by a reduction in RBF due to an enhanced neurohumoral release of vasoconstrictive hormones.

Electrolyte homeostasis was found to be well-preserved during and after the marathon. There were no significant changes in Na^+ and Cl^- described to be the most popular electrolyte disturbances with marathon running [27]. But there were slight increases in Ca^{2+} and Mg^{2+} which partially may be explained by the ingestion of unstandardized drinking solutions containing different amounts of electrolytes. The significant increase in serum K^+ may reflect reduced K^+ excretion obvious by an enhanced TTKG due to the exercise-activated RAAS.

The finding of post-exercise proteinuria is a common phenomenon [6,21–24]. The observed type of mixed glomerular-tubular proteinuria confirms previous data gained in various fields of sports. The available information demonstrates post-exercise proteinuria to be of the mixed type and the major part of the excreted protein to be of plasma origin in any situation of heavy exercise [21,24]. This increased clearance of mixed plasma proteins suggests that both enhanced glomerular permeability and partial inhibition of tubular reabsorption of macromolecules follow prolonged strenuous cycling. The moderate scale of proteinuria manifests once more that the extent of post-exercise proteinuria is more dependent on the intensity than on the duration of the effort [21,22].

We are aware that the interpretation of some study results may only be done with caution. For logistic reasons we could not perform hormone analyses and measurements of creatinine or insulin clearances because it is methodically impossible to get 24h-urine collections from athletes competing in a marathon race. We therefore do not dispose of distinct information about collected 24h-excretions either. Being aware of this limitation we concentrated on parameters unaffected by any CCr measurements, i.e. $FENa^+$, FEUA and TTKG. At least it is worth mentioning that the interpretation of all post-race changes in serum constituents must take account of the post-exercise PV expansion of 10.8%. For this reason the slight reduction in renal function could even be underestimated to a very small extent.

Despite these limitations our study is the first to investigate the physiological renal effects of competitive marathon cycling. The results obtained give evidence that strenuous long-term cycling alters renal function only on a minimal scale. In contrast to marathon running, marathon cycling appears to have a smaller impact on the decline of renal function probably due to a better preserved fluid balance and a markedly minor skeletal muscle damage.

References

[1] Altenkirch HU, Gerzer R, Kirsch KA, Weil J, Heyduck B, Schultes I, Rocker L. Effect of prolonged physical exercise on fluid regulating hormones. Eur J Appl Physiol 1990; 61: 209 – 213
[2] Armstrong RB. Muscle damage and endurance events. Sports Med 1986; 3: 370 – 381
[3] Castenfors J, Mossfeldt F, Piscator M. Effect of prolonged heavy exercise on renal function and urinary protein excretion. Acta Physiol Scand 1967; 70: 194 – 206
[4] Costill DL. Sweating: its composition and effects on body fluids. Ann N Y Acad Sci 1977; 301: 160 – 174
[5] Dancaster CP, Duckworth WC, Roper CJ. Nephropathy in marathon runners. S Afr Med J 1969; 43: 758 – 759
[6] Dancaster CP, Whereat SJ. Renal function in marathon runners. S Afr Med J 1971; 45: 547 – 551
[7] Decombaz J, Reinhardt P, Anantharaman K, von Glutz G, Poortmans JR. Biochemical changes in a 100 km run: free amino acids, urea, and creatinine. Eur J Appl Physiol 1979; 41: 61 – 72
[8] Fallon KE, Sivyer G, Sivyer K, Dare A. The biochemistry of runners in a 1600 km ultramarathon. Br J Sports Med 1999; 33: 264 – 269
[9] Gault MH, Longerich LL, Harnett JD, Wesolowski C. Predicting glomerular function from adjusted serum creatinine [editorial]. Nephron 1992; 62: 249 – 256
[10] Green HJ, Fraser IG. Differential effects of exercise intensity on serum uric acid concentration. Med Sci Sports Exerc 1988; 20: 55 – 59
[11] Irving RA, Noakes TD, Burger SC, Myburgh KH, Querido D, van Zyl SR. Plasma volume and renal function during and after ultramarathon running [see comments]. Med Sci Sports Exerc 1990; 22: 581 – 587
[12] Irving RA, Noakes TD, Irving GA, van Zyl SR. The immediate and delayed effects of marathon running on renal function. J Urol 1986; 136: 1176 – 1180
[13] Irving RA, Noakes TD, Raine RI, van Zyl SR. Transient oliguria with renal tubular dysfunction after a 90 km running race. Med Sci Sports Exerc 1990; 22: 756 – 761
[14] Kreider RB. Physiological considerations of ultraendurance performance. Int J Sport Nutr 1991; 1: 3 – 27
[15] MacSearraigh ETM, Kallmeyer J, Schiff HB. Acute renal failure in marathon runners. Nephron 1979; 24: 236 – 240
[16] Millard RW, Higgins CB, Franklin D, Vatner SF. Regulation of the renal circulation during severe exercise in normal dogs and dogs with experimental heart failure. Circ Res 1972; 31: 881 – 888
[17] Neviackas JA, Bauer JH. Renal function abnormalities induced by marathon running. South Med J 1981; 74: 1457 – 1460
[18] Neumayr G, Pfister R, Mitterbauer G, Gaenzer H, Joannidis M, Eibl G, Hoertnagl H. Short-term effects of prolonged strenuous endurance exercise on the level of haematocrit in amateur cyclists. Int J Sports Med 2002; 23: 158 – 161
[19] Neumayr G, Pfister R, Mitterbauer G, Gaenzer H, Sturm W, Eibl G, Hoertnagl H. Exercise intensity of cycle-touring events. Int J Sports Med 2002; 23: 505 – 509
[20] Ounpuu S. The biomechanics of running: a kinematic and kinetic analysis. Instr Course Lect 1990; 39: 305 – 318
[21] Poortmans JR. Exercise and renal function. Sports Med 1984; 1: 125 – 153
[22] Poortmans JR. Postexercise proteinuria in humans. Facts and mechanisms. JAMA 1985; 253: 236 – 240
[23] Poortmans JR, Brauman H, Staroukine M, Verniory A, Decaestecker C, Leclercq R. Indirect evidence of glomerular/tubular mixed-type postexercise proteinuria in healthy humans. Am J Physiol 1988; 254: F277 – F283
[24] Poortmans JR, Vancalck B. Renal glomerular and tubular impairment during strenuous exercise in young women. Eur J Clin Invest 1978; 8: 175 – 178
[25] Refsum HE, Stromme SB. Relationship between urine flow, glomerular filtration, and urine solute concentrations during prolonged heavy exercise. Scand J Clin Lab Invest 1975; 35: 775 – 780
[26] Refsum HE, Stromme SB. Renal osmol clearance during prolonged heavy exercise. Scand J Clin Lab Invest 1978; 38: 19 – 22
[27] Schmidt W, Rojas J, Boning D, Bernal H, Garcia S, Garcia O. Plasma-electrolytes in natives to hypoxia after marathon races at different altitudes. Med Sci Sports Exerc 1999; 31: 1406 – 1413
[28] Steiner RW. Interpreting the fractional excretion of sodium. Am J Med 1984; 77: 699 – 702
[29] Strauss MB, Davies RK, Rosenbaum JD, Rossmeisl EC. Water diuresis produced during recumbency by the intravenous infusion of isotonic saline solution. J Clin Invest 1951; 30: 862 – 868
[30] Suzuki M, Sudoh M, Matsubara S, Kawakami K, Shiota M, Ikawa S. Changes in renal blood flow measured by radionuclide angiography following exhausting exercise in humans. Eur J Appl Physiol 1996; 74: 1 – 7
[31] Virvidakis C, Loukas A, Mayopoulou-Symvoulidou M, Mountokalakis T. Renal responses to bicycle exercise in trained athletes: influence of exercise intensity. Int J Sports Med 1986; 7: 86 – 88
[32] West ML, Marsden PA, Richardson RM, Zettle RM, Halperin ML. New clinical approach to evaluate disorders of potassium excretion. Miner Electrolyte Metab 1986; 12: 234 – 238
[33] Williams KR. The relationship between mechanical and physiological energy estimates. Med Sci Sports Exerc 1985; 17: 317 – 325