

RESEARCH ARTICLE

Open Access

# Hydrogen-rich water inhibits glucose and $\alpha,\beta$ -dicarbonyl compound-induced reactive oxygen species production in the SHR.Cg-*Lep<sup>cp</sup>*/NDmcr rat kidney

Masanori Katakura<sup>†</sup>, Michio Hashimoto<sup>\*†</sup>, Yoko Tanabe and Osamu Shido

## Abstract

**Background:** Reactive oxygen species (ROS) production induced by  $\alpha,\beta$ -dicarbonyl compounds and advanced glycation end products causes renal dysfunction in patients with type 2 diabetes and metabolic syndrome. Hydrogen-rich water (HRW) increases the H<sub>2</sub> level in blood and tissues, thus reducing oxidative stress in animals as well as humans. In this study, we investigated the effects of HRW on glucose- and  $\alpha,\beta$ -dicarbonyl compound-induced ROS generation in vitro and in vivo.

**Methods:** Kidney homogenates from Wistar rats were incubated in vitro with glucose and  $\alpha,\beta$ -dicarbonyl compounds containing HRW, following which ROS levels were measured. In vivo animal models of metabolic syndrome, SHR.Cg-*Lep<sup>cp</sup>*/NDmcr rats, were treated with HRW for 16 weeks, following which renal ROS production and plasma and renal  $\alpha,\beta$ -dicarbonyl compound levels were measured by liquid chromatograph mass spectrometer.

**Results:** HRW inhibited glucose- and  $\alpha,\beta$ -dicarbonyl compound-induced ROS production in kidney homogenates from Wistar rats in vitro. Furthermore, SHR.Cg-*Lep<sup>cp</sup>*/NDmcr rats treated with HRW showed a 34% decrease in ROS production. Moreover, their renal glyoxal, methylglyoxal, and 3-deoxyglucosone levels decreased by 81%, 77%, and 60%, respectively. Positive correlations were found between renal ROS levels and renal glyoxal ( $r = 0.659$ ,  $p = 0.008$ ) and methylglyoxal ( $r = 0.782$ ,  $p = 0.001$ ) levels.

**Conclusion:** These results indicate that HRW inhibits the production of  $\alpha,\beta$ -dicarbonyl compounds and ROS in the kidneys of SHR.Cg-*Lep<sup>cp</sup>*/NDmcr rats. Therefore, it has therapeutic potential for renal dysfunction in patient with type 2 diabetes and metabolic syndrome.

**Keywords:** Hydrogen-rich water,  $\alpha,\beta$ -dicarbonyl compounds, Oxidative stress, Metabolic syndrome model, Advanced glycation end products

## Background

Nonenzymatic glycation of proteins and the Maillard reaction result in the formation of advanced glycation end products (AGEs), which are associated with the pathogenesis of type 2 diabetes [1]. During the formation of AGEs,  $\alpha,\beta$ -dicarbonyl compounds such as glyoxal, methylglyoxal, and 3-deoxyglucosone are produced as reactive intermediates [2]. Patients with type 2 diabetes

have increased plasma levels of these compounds [3]. Moreover, AGEs [4, 5], and  $\alpha,\beta$ -dicarbonyl compounds [6] produce reactive oxygen species (ROS). Oxidative stress is of particular interest in the pathogenesis of diabetic nephropathy [7], the latter being the leading cause of end-stage renal disease.

Molecular hydrogen (H<sub>2</sub>), a potent free radical scavenger, selectively reduces the levels of the hydroxyl radical and peroxynitrite, which is the most cytotoxic ROS [8]. Consumption of water saturated with H<sub>2</sub> [H<sub>2</sub>-rich water (HRW)] increases the blood H<sub>2</sub> level and reduces renal oxidative stress in mice with cisplatin-induced nephrotoxicity

\* Correspondence: michio1@med.shimane-u.ac.jp

<sup>†</sup>Equal contributors

Department of Environmental Physiology, Shimane University Faculty of Medicine, Izumo, Shimane 693-8501, Japan

[9], rats with chronic kidney disease [10], and rats with chronic allograft nephropathy [11].

We previously demonstrated that HRW confers considerable benefits against renal abnormalities in SHR.Cg-*Lep<sup>r</sup><sup>cp</sup>*/NDmcr (SHRcp) rats, which are metabolic syndrome models, at least by preventing glomerulosclerosis and ameliorating creatinine clearance [12]. Furthermore, a sufficient supply of HRW may prevent or delay the development and progression of type 2 diabetes [13] and metabolic syndrome [14] by protecting against oxidative stress. However, the exact mechanisms of the beneficial effects of HRW on diabetic nephropathy remain unknown.

Given the potent free radical-scavenging activity of H<sub>2</sub>, we hypothesized that HRW may attenuate the production of  $\alpha,\beta$ -dicarbonyl compounds as well as the production of ROS from AGEs and  $\alpha,\beta$ -dicarbonyl compounds. In this study, we investigated whether HRW could inhibit glucose- and  $\alpha,\beta$ -dicarbonyl compound-induced ROS production in vitro and in vivo.

## Methods

### Animals

Ten-week-old male Wistar rats (Clea Japan, Inc., Japan) were used for the in vitro experiments. Five-week-old male SHRcp rats (Disease Model Cooperative Research Association, Japan) were randomly divided into 2 groups: the HRW-treated group (n = 12), which received oral HRW, and the control group (n = 12), which received distilled water. Both groups were treated for 16 weeks as described previously [12]. All rats were housed under controlled temperature (23 ± 2°C)- and humidity (50% ± 10%)- with a 12-h light-dark cycle. The Wistar rats were fed normal rat chow (CE-2, Oriental Yeast Co., Ltd, Japan) while the SHRcp rats were fed Quick Fat (Clea Japan, Inc.) with ad libitum access to sterile-water or HRW (Additional file 1: Table S1).

All rats were anesthetized with intraperitoneal sodium pentobarbital (65 mg/kg), following which their kidneys were removed, immediately frozen in liquid nitrogen and stored at -30°C until further use. The kidneys were homogenized with phosphate buffer (pH, 7.4) in a Teflon homogenizer. The homogenates were immediately frozen in liquid nitrogen and stored at -30°C until use. All animal experiments were conducted in accordance with the procedures outlined in the Guidelines for Animal Experimentation of Shimane University, compiled from the Guidelines for Animal Experimentation of the Japanese Association for Laboratory Animal Science.

### Generation of HRW

Nakao et al. have described the production and characterization of HRW [14]. HRW was prepared by dipping a plastic-shelled product (stick) comprising metallic magnesium (99.9% pure) and natural stones (Doctor SUISOSUI®;

Friendear Inc., Japan) into distilled water. HRW was freshly prepared every other day in a 200-mL bottle containing the stick, and the H<sub>2</sub> concentration was maintained between 0.3 and 0.4 ppm during the experiment.

### In vitro experimentation

#### Fenton reaction

Kidney homogenates were incubated with or without HRW in PBS containing 2 mM FeSO<sub>4</sub> and 5 mM H<sub>2</sub>O<sub>2</sub> for 60 min at 37°C. After the reaction, one aliquot was used for lipid peroxide (LPO) measurement and a second aliquot was added to ice-cold PBS for ROS measurement.

#### Treatment with glucose and $\alpha,\beta$ -dicarbonyl compounds

Kidney homogenates were incubated with or without HRW in PBS containing glucose (1, 10, or 100 mM; Wako Pure Chemical Industries, Japan), glyoxal (2, 20, or 200  $\mu$ M; Nacalai Tesque, Inc., Japan), methylglyoxal (2, 20, or 200  $\mu$ M; Sigma-Aldrich, USA), or 3-deoxyglucosone (2, 20, or 200  $\mu$ M, Wako Pure Chemical Industries) for 60 min at 37°C. Ice-cold PBS was then added and ROS levels were measured.

#### LPO measurement

LPO concentrations were measured using the thiobarbituric acid reactive substance assay as described previously [15], and they were expressed as moles of malondialdehyde. Malondialdehyde levels were calculated relative to a standard preparation of 1,1,3,3-tetraethoxypropane.

#### ROS measurement

ROS levels were measured as previously described [16]. In brief, kidney samples were centrifuged at 12,500 g for 10 min at 4°C. The pellets were resuspended in PBS and sonicated for 3 min in ice-cold water. The substrate 2',7'-dichlorofluorescein diacetate (Sigma-Aldrich) was mixed with the resultant samples, and fluorescence was monitored every 10 min for 60 min in the dark at 37°C. Fluorescence was measured with a DTX 880 multimode detector (Beckman Coulter, Inc., USA) using excitation and emission filters at 488 and 543 nm, respectively. 2',7'-Dichlorofluorescein (Sigma-Aldrich) was used as the standard. Data were expressed as dichlorofluorescein production per minute per milligram of protein. Protein concentration was determined by using the Lowry method.

#### Measurement of $\alpha,\beta$ -dicarbonyl compounds

The levels of  $\alpha,\beta$ -dicarbonyl compounds in the kidneys and plasma of the SHRcp rats were measured as described with a slight modification [3]. In brief, glyoxal, methylglyoxal, and 3-deoxyglucosone solutions in 10 mM phosphate buffer (pH, 7.4) with 0.005% 3,4-hexanedione (Tokyo Kasei Organic Chemicals, Japan) as internal standard were

incubated overnight with 0.01% 2,3-diaminonaphthalene (Tokyo Kasei Organic Chemicals) at 4°C. The reaction mixtures were extracted with ethyl acetate, and the organic layers were dried under nitrogen gas. The dried extracts were reconstituted with methanol and injected into a liquid chromatograph mass spectrometer (LC-MS/MS) system. HPLC was combined with ESI-MS in a TSQ Quantum mass spectrometer (Thermo Fisher Scientific K. K., Japan). HPLC was conducted in a Luna 5u C18(2) 100 Å LC column (150 × 2.0 mm, Phenomenex, USA) at 30°C. Samples were eluted with a mobile phase composed of acetonitrile methanol (4:1, v/v) and water acetic acid (100:0.1, v/v) in a 10:90 ratio for 5 min, ramped up to a 100:0 ratio after 25 min, and held for 10 min at a flow rate of 0.1 mL/min. MS/MS was conducted in positive ion mode, and 2,3-diaminonaphthalene derivatives of methylglyoxal (m/z 195 > 127), glyoxal (m/z 181 > 127), 3-deoxyglucosone (m/z 285 > 221), and 3,4-hexanedione (m/z 237 > 169) were detected and quantified by selected reaction monitoring.

#### Statistical analysis

Results are expressed as means ± SEM. Data were analyzed by Dunnett's multiple comparison test and Student's *t*-test. Differences between groups were considered significant at *p*-values less than 0.05. All statistical analyses were performed with PASW Statistics 18.0 (IBM-SPSS, Inc., USA).

### Results

#### Fenton reaction-induced ROS and LPO production

ROS and LPO levels by 82% and 62%, respectively, in the kidney homogenates incubated with H<sub>2</sub>O<sub>2</sub> and FeSO<sub>4</sub>; however, their production was inhibited by

treatment with HRW (Figure 1). These results are consistent with those of a previous study in which H<sub>2</sub> selectively reduced the levels of the hydroxyl radical [8] generated by the Fenton reaction.

#### Glucose- and α,β-dicarbonyl compound-induced ROS production

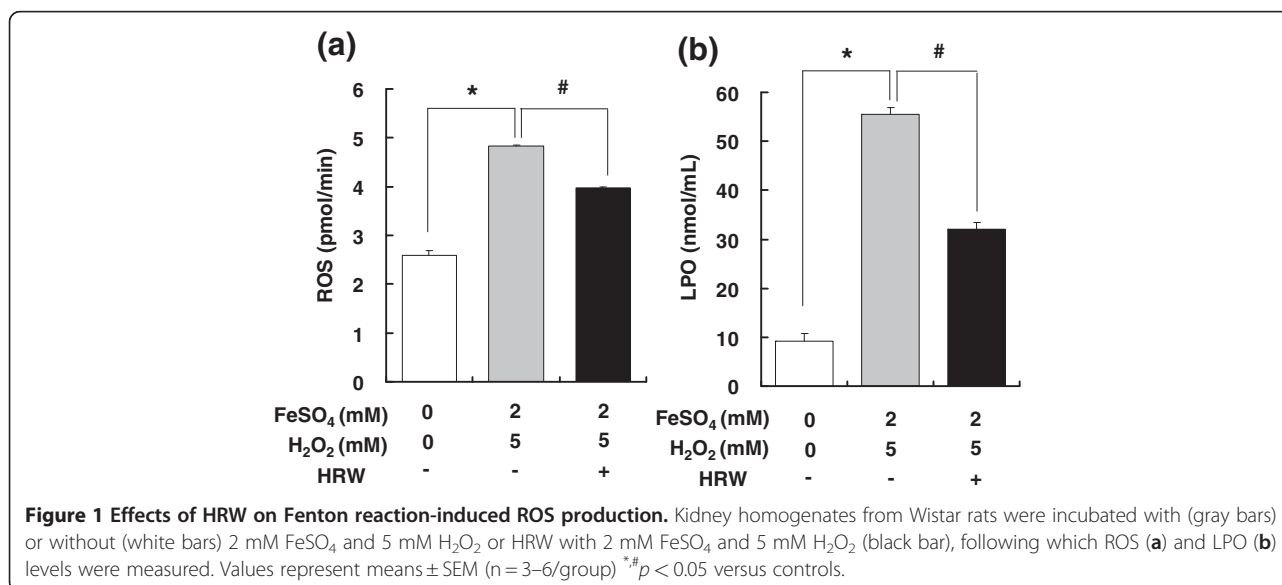
ROS levels were significantly increased after incubation with glucose or α,β-dicarbonyl compounds; however, their production was inhibited by treatment with HRW (Figure 2). These results indicate that HRW inhibited ROS production induced by glucose and α,β-dicarbonyl compounds.

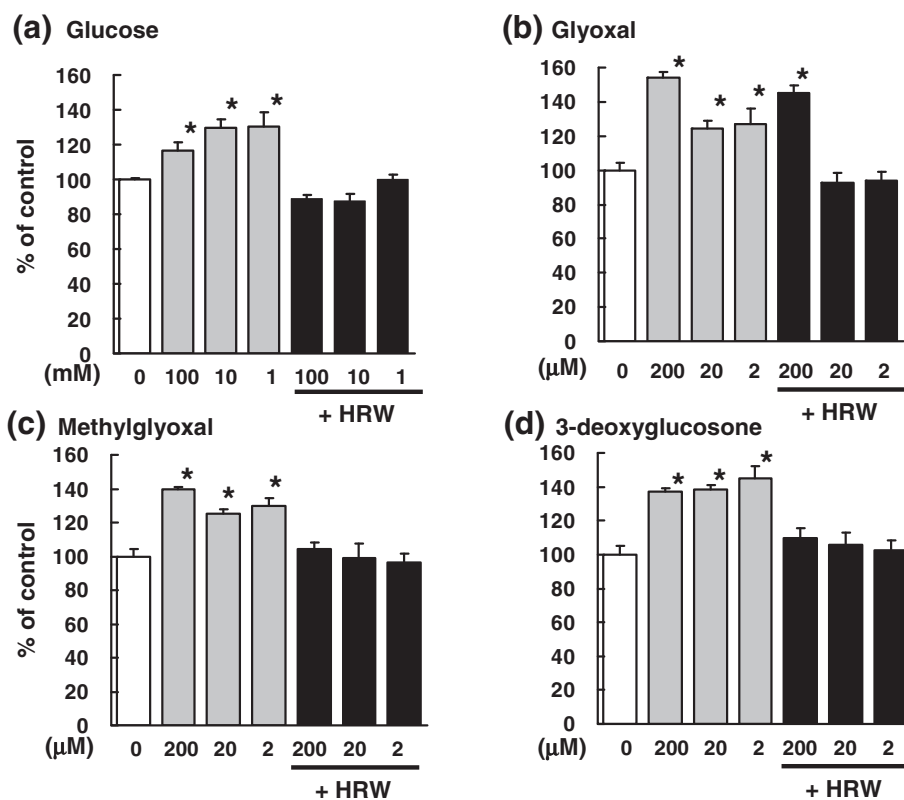
#### Renal ROS levels

As a result of the in vitro findings (Figures 1 and 2), renal ROS levels were measured in the SHRcp rats after treatment with HRW for 16 weeks. The renal ROS levels were significantly decreased by 34% in these treated animals compared with the controls (Figure 3), indicating that HRW inhibited ROS production in vivo.

#### Plasma and renal α,β-dicarbonyl compound levels

Glyoxal and methylglyoxal levels, but not 3-deoxyglucosone levels, were significantly decreased in the plasma of HRW-treated SHRcp rats compared with their control counterparts (Figure 4a–c). Furthermore, the renal levels of glyoxal, methylglyoxal, and 3-deoxyglucosone decreased by 81%, 77% and 60%, respectively, in the HRW-treated group (Figure 4d–f). Positive correlations were found between renal ROS levels and renal glyoxal ( $r = 0.659$ ,  $p = 0.008$ ) and methylglyoxal ( $r = 0.782$ ,  $p = 0.001$ ) levels; however, 3-deoxyglucosone levels ( $r = 0.202$ ,  $p = 0.470$ ) were





**Figure 2** Effects of HRW on glucose- and  $\alpha,\beta$ -dicarbonyl compound-induced ROS production. Kidney homogenates from Wistar rats were incubated with (a) glucose (1, 10, or 100 mM), (b) glyoxal (2, 20, or 200  $\mu$ M), (c) methylglyoxal (2, 20, or 200  $\mu$ M), or (d) 3-deoxyglucosone (2, 20, or 200  $\mu$ M). Then, ROS levels were measured. Values represent means  $\pm$  SEM ( $n = 3-6$ /group), \* $p < 0.05$  versus controls.

comparable. These results indicated that HRW inhibit the production of  $\alpha,\beta$ -dicarbonyl compounds and ROS in the kidneys of the SHRcp rats.

## Discussion

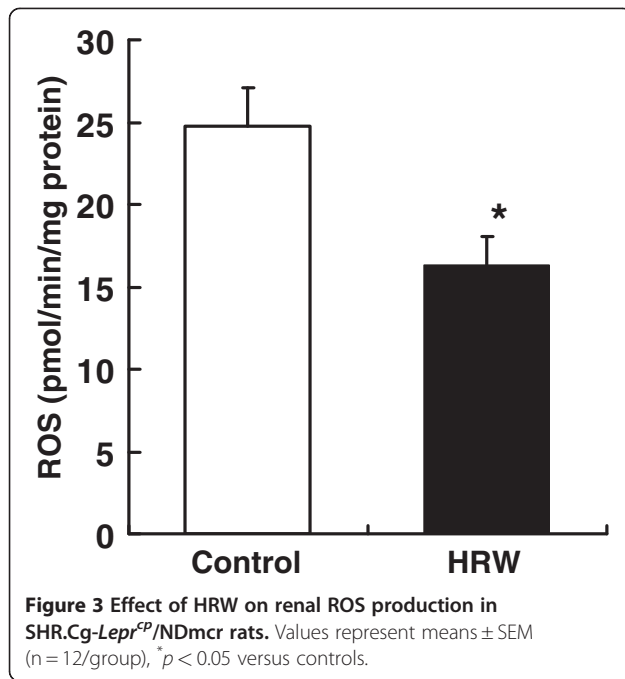
The present study revealed that HRW prevented glucose- and  $\alpha,\beta$ -dicarbonyl compound-induced ROS production in vitro (Figure 2) and in vivo (Figure 3). In the in vivo study, HRW decreased the levels of  $\alpha,\beta$ -dicarbonyl compounds in the plasma and kidney (Figure 4).

$\alpha,\beta$ -Dicarbonyl compounds reportedly form from degradation of glucose in 200 mM PBS (pH, 7.4) [17]. These compounds can produce free radicals [7, 18] such as the hydroxyl radical [19], peroxynitrate [20], and the acetyl radical [21].  $H_2$  selectively decreases the levels of the hydroxyl radical and peroxynitrite [8]. Data from the present study showed that HRW inhibited ROS production induced by the Fenton reaction and  $\alpha,\beta$ -dicarbonyl compounds. Taken together, these results suggest that HRW decreases hydroxyl radical and peroxynitrate production induced by  $\alpha,\beta$ -dicarbonyl compounds.

$\alpha,\beta$ -Dicarbonyl compound- and glucose-induced oxidative stress is considered to be a cause of renal dysfunction in vivo. Methylglyoxal and glucose induce renal

oxidative damage and podocyte apoptosis in Zucker diabetic fatty rats [22] and *db/db* mice [23]. Patients with type 2 diabetes have increased plasma levels of these compounds [3]. In the present study, we investigated whether HRW could inhibit  $\alpha,\beta$ -dicarbonyl compound-induced oxidative stress in vivo. SHRcp rats were chosen for the present study because they exhibit several metabolic disorders, such as hypertension, hyperglycemia, hyperinsulinemia, and hyperlipidemia [24]. Histologically, islet area expansion, fatty liver, and glomerulosclerosis can be observed in these rats. Therefore, they are considered to be a suitable animal model for renal dysfunction with the metabolic syndrome. Renal ROS levels were significantly decreased in the HRW-treated SHRcp rats compared with the control group (Figure 3). Furthermore, glyoxal and methylglyoxal levels in plasma and glyoxal, methylglyoxal, and 3-deoxyglucosone levels in the kidney were significantly decreased in HRW-treated animals compared with the control group (Figure 4). These results indicate that HRW inhibits ROS production by inhibiting  $\alpha,\beta$ -dicarbonyl compound production.

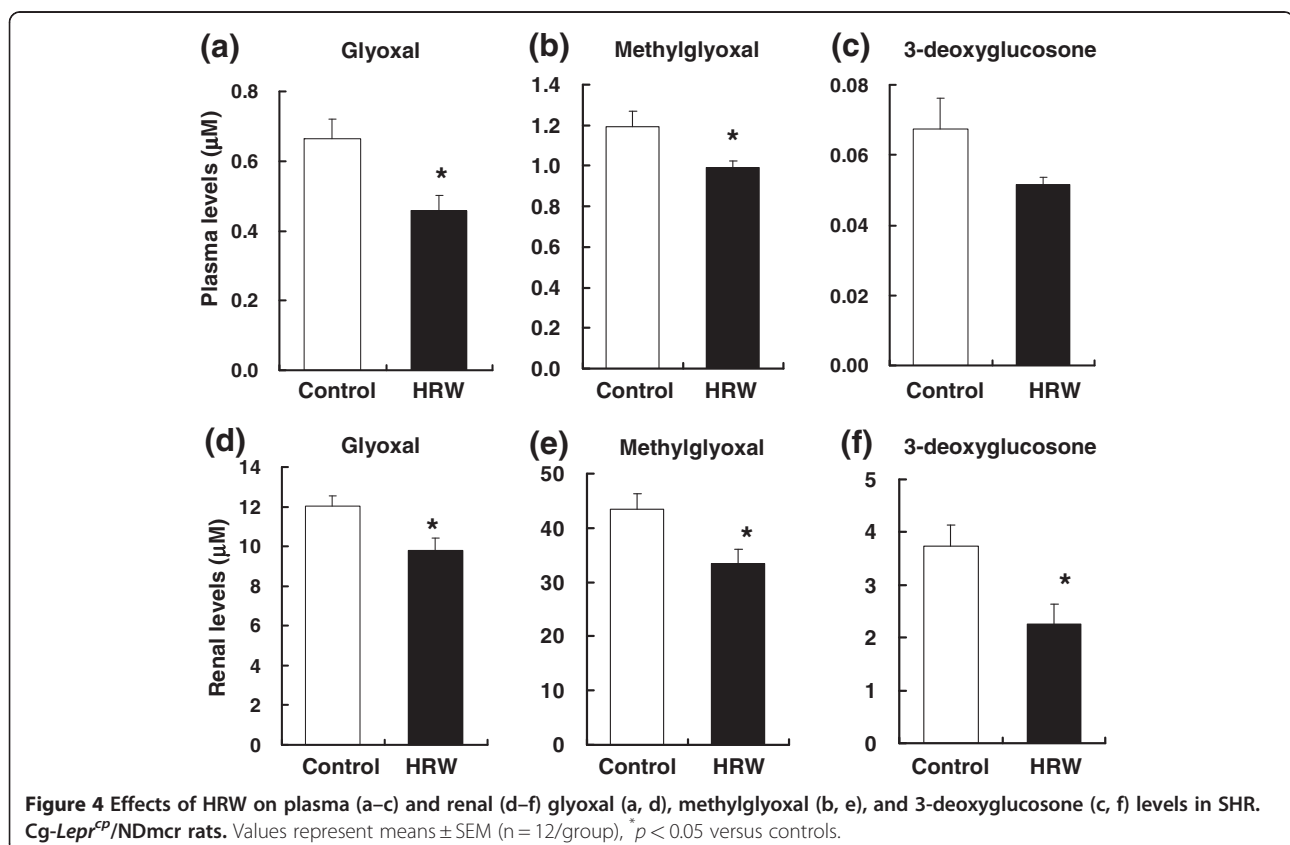
Renoprotection does not necessarily depend on blood pressure or glycemic control [25]. Caloric restriction



control in SHRcp rats. These reports indicate that renoprotection is associated with decreased AGE formation and oxidative stress, thus suggesting that they are potential therapeutic strategies for renal dysfunction in patients with type 2 diabetes and metabolic syndrome. We previously reported that HRW does not affect blood pressure or blood glucose levels but prevents glomerulosclerosis in SHRcp rats [12]. In the present study, we noted that HRW inhibited the production of  $\alpha,\beta$ -dicarbonyl compounds and ROS in these rats, suggesting that HRW has a potential therapeutic application for patient with renal dysfunction.

There are other possible molecular mechanisms to prevent oxidative stress cause by HRW. Kawamura et al. [30] have reported that in lung allograft in rats, H<sub>2</sub> induces heme oxygenase-1 expression, decreases proinflammatory cytokines and the proapoptotic protein Bax, and increases expression of antiapoptotic protein Bcl-2. H<sub>2</sub> reduces the binding of several transcription factors such as AP1 and NF $\kappa$ B to the iNOS promoter via inhibition of signal transduction in macrophages [31]. These reports suggest that the molecular target for HRW not only inhibits ROS generation but also induces gene expression of antioxidative enzymes at the transcriptional level. Further studies are necessary to explore these effects.

[26] and treatment with angiotensin II receptor blocker [27], pioglitazone [28], or cobalt [29] protect against renal dysfunction without blood pressure or glycemic



It has been reported that consumption of HRW for 8 weeks increases superoxide dismutase levels by 39% and decreases thiobarbituric acid reactive substance levels by 43% in the urine of subjects with potential metabolic syndrome [14]. Consumption of HRW is also associated with a significant decrease in the urinary levels of 8-isoprostanes, which are endogenous lipid peroxidation products [13]. These results indicate that HRW may have antioxidant activity in humans. Further studies are necessary to confirm the effects of HRW on renal dysfunction associated with type 2 diabetes and metabolic syndrome in humans.

Aminoguanidine, a prototype AGE formation inhibitor, acts by scavenging  $\alpha,\beta$ -dicarbonyl compounds. Aminoguanidine has been shown to inhibit the formation of AGEs and slow the progression of diabetic nephropathy in animal models [32, 33]. It also significantly decreases proteinuria in treated subjects [34]. However, aminoguanidine is a nonspecific AGE inhibitor that also inhibits nitric oxide synthase [35] and causes DNA damage [36]. Aminoguanidine cannot be used for the treatment of diabetic nephropathy because of safety concerns, and additional clinical studies are required to address the safety and efficacy of other types of AGE inhibitors [37]. On the other hand, consumption of HRW had no adverse effects on hematological parameters and biometric parameters during an 8-week study period in humans [14], suggesting that HRW is safe.

## Conclusions

In conclusion, HRW inhibits renal ROS production induced by glucose and  $\alpha,\beta$ -dicarbonyl compounds in vitro and renal ROS and  $\alpha,\beta$ -dicarbonyl compound production in vivo. Therefore, it has therapeutic potential for the treatment of renal dysfunction in patients with type 2 diabetes and potential metabolic syndrome.

## Additional file

**Additional file 1: Table S1.** Composition of the MF diet and Quick Fat diet

### Abbreviations

AGEs: advanced glycation end products; HRW: H<sub>2</sub>-rich water; H<sub>2</sub>: Molecular hydrogen; LPO: lipid peroxide; ROS: reactive oxygen species; SHRcp: SHR.Cg-Lep<sup>cp</sup>/NDmcr.

### Competing interests

The author(s) declare that they have no competing interests

### Authors' contributions

MK participated in the design of the study and carried out the incubation studies, LC/MS analysis, and drafted the manuscript. YT performed the statistical analysis. OS participated in the sequence alignment. MH conceived of the study, and participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

## Acknowledgements

We thank Friendear Inc. (Tokyo, Japan) for the metallic magnesium sticks (Doctor SUIOSUI<sup>®</sup>). This study was supported in part by a Grant-in-Aid for Scientific Research (C) (#23500955 to MH) and by a Grant-in-Aid for Young Scientists (B) (#24790234 to MK). The authors would like to thank Enago (www.enago.jp) for the English language review.

Received: 8 May 2012 Accepted: 28 June 2012

Published: 9 July 2012

## References

1. Bierhaus A, Hofmann MA, Ziegler R, Nawroth PP: AGEs and their interaction with AGE-receptors in vascular disease and diabetes mellitus. I. The AGE concept. *Cardiovasc Res* 1998, **37**:586–600.
2. Weiss MF, Erhard P, Kader-Attia FA, Wu YC, Deoreo PB, Araki A, Glomb MA, Monnier VM: Mechanisms for the formation of glycoxidation products in end-stage renal disease. *Kidney Int* 2000, **57**:2571–2585.
3. Odani H, Shinzato T, Matsumoto Y, Usami J, Maeda K: Increase in three alpha, beta-dicarbonyl compound levels in human uremic plasma: specific in vivo determination of intermediates in advanced Maillard reaction. *Biochem Biophys Res Commun* 1999, **256**:89–93.
4. Tan AL, Forbes JM, Cooper ME: AGE, RAGE, and ROS in diabetic nephropathy. *Semin Nephrol* 2007, **27**:130–143.
5. Kovacic P, Somanathan R: Cell signaling and receptors in toxicity of advanced glycation end products (AGEs): alpha-dicarbonyls, radicals, oxidative stress and antioxidants. *J Recept Signal Transduct Res* 2011, **31**:332–339.
6. Kalapos MP: The tandem of free radicals and methylglyoxal. *Chem Biol Interact* 2008, **171**:251–271.
7. Stanton RC: Oxidative stress and diabetic kidney disease. *Curr Diabetes Rep* 2011, **11**:330–336.
8. Ohsawa I, Ishikawa M, Takahashi K, Watanabe M, Nishimaki K, Yamagata K, Katsura K, Katayama Y, Asoh S, Ohta S: Hydrogen acts as a therapeutic antioxidant by selectively reducing cytotoxic oxygen radicals. *Nat Med* 2007, **13**:688–694.
9. Nakashima-Kamimura N, Mori T, Ohsawa I, Asoh S, Ohta S: Molecular hydrogen alleviates nephrotoxicity induced by an anti-cancer drug cisplatin without compromising anti-tumor activity in mice. *Cancer Chemother Pharmacol* 2009, **64**:753–761.
10. Zhu WJ, Nakayama M, Mori T, Nakayama K, Katoh J, Murata Y, Sato T, Katsura K, Ito S: Intake of water with high levels of dissolved hydrogen (H<sub>2</sub>) suppresses ischemia-induced cardio-renal injury in Dahl salt-sensitive rats. *Nephrol Dial Transplant* 2010, **26**:2112–2118.
11. Cardinal JS, Zhan J, Wang Y, Sugimoto R, Tsung A, McCurry KR, Billiar TR, Nakao A: Oral hydrogen water prevents chronic allograft nephropathy in rats. *Kidney Int* 2010, **77**:101–109.
12. Hashimoto M, Katakura M, Nabika T, Tanabe Y, Hossain S, Tsuchikura S, Shido O: Effects of hydrogen-rich water on abnormalities in a SHR.Cg-Lep<sup>cp</sup>/NDmcr rat - a metabolic syndrome rat model. *Med Gas Res* 2011, **1**:26.
13. Kajiyama S, Hasegawa G, Asano M, Hosoda H, Fukui M, Nakamura N, Kitawaki J, Imai S, Nakano K, Ohta M, et al: Supplementation of hydrogen-rich water improves lipid and glucose metabolism in patients with type 2 diabetes or impaired glucose tolerance. *Nutr Res* 2008, **28**:137–143.
14. Nakao A, Toyoda Y, Sharma P, Evans M, Guthrie N: Effectiveness of hydrogen rich water on antioxidant status of subjects with potential metabolic syndrome-an open label pilot study. *J Clin Biochem Nutr* 2010, **46**:140–149.
15. Ohkawa H, Ohishi N, Yagi K: Assay for lipid peroxides in animal tissues by thiobarbituric acid reaction. *Anal Biochem* 1979, **95**:351–358.
16. Montoliu C, Valles S, Renau-Piqueras J, Guerri C: Ethanol-induced oxygen radical formation and lipid peroxidation in rat brain: effect of chronic alcohol consumption. *J Neurochem* 1994, **63**:1855–1862.
17. Usui T, Yanagisawa S, Ohguchi M, Yoshino M, Kawabata R, Kishimoto J, Arai Y, Aida K, Watanabe H, Hayase F: Identification and determination of alpha-dicarbonyl compounds formed in the degradation of sugars. *Biosci Biotechnol Biochem* 2007, **71**:2465–2472.
18. Desai KM, Wu L: Free radical generation by methylglyoxal in tissues. *Drug Metabol Drug Interact* 2008, **23**:151–173.

19. da Silva G: **Hydroxyl radical regeneration in the photochemical oxidation of glyoxal: kinetics and mechanism of the HC(O)CO + O(2) reaction.** *Phys Chem Chem Phys* 2010, **12**:6698–6705.
20. Massari J, Tokikawa R, Medinas DB, Angeli JP, Di Mascio P, Assuncao NA, Bechara EJ: **Generation of singlet oxygen by the glyoxal-peroxynitrite system.** *J Am Chem Soc* 2011, **133**:20761–20768.
21. Massari J, Tokikawa R, Zanolli L, Tavares MF, Assuncao NA, Bechara EJ: **Acetyl radical production by the methylglyoxal-peroxynitrite system: a possible route for L-lysine acetylation.** *Chem Res Toxicol* 2010, **23**:1762–1770.
22. Kim J, Sohn E, Kim CS, Kim JS: **Renal podocyte apoptosis in Zucker diabetic fatty rats: involvement of methylglyoxal-induced oxidative DNA damage.** *J Comp Pathol* 2011, **144**:41–47.
23. Susztak K, Raff AC, Schiffer M, Bottinger EP: **Glucose-induced reactive oxygen species cause apoptosis of podocytes and podocyte depletion at the onset of diabetic nephropathy.** *Diabetes* 2006, **55**:225–233.
24. Yamaguchi Y, Yoshikawa N, Kagota S, Nakamura K, Haginaka J, Kunitomo M: **Elevated circulating levels of markers of oxidative-nitrate stress and inflammation in a genetic rat model of metabolic syndrome.** *Nitric Oxide* 2006, **15**:380–386.
25. Miyata T, Izuhara Y: **Inhibition of advanced glycation end products: an implicit goal in clinical medicine for the treatment of diabetic nephropathy?** *Ann N Y Acad Sci* 2008, **1126**:141–146.
26. Nangaku M, Izuhara Y, Usuda N, Inagi R, Shibata T, Sugiyama S, Kurokawa K, van Ypersele de Strihou C, Miyata T: **In a type 2 diabetic nephropathy rat model, the improvement of obesity by a low calorie diet reduces oxidative/carbonyl stress and prevents diabetic nephropathy.** *Nephrol Dial Transplant* 2005, **20**:2661–2669.
27. Izuhara Y, Nangaku M, Inagi R, Tominaga N, Aizawa T, Kurokawa K, van Ypersele de Strihou C, Miyata T: **Renoprotective properties of angiotensin receptor blockers beyond blood pressure lowering.** *J Am Soc Nephrol* 2005, **16**:3631–3641.
28. Ohtomo S, Izuhara Y, Takizawa S, Yamada N, Kakuta T, van Ypersele de Strihou C, Miyata T: **Thiazolidinediones provide better renoprotection than insulin in an obese, hypertensive type II diabetic rat model.** *Kidney Int* 2007, **72**:1512–1519.
29. Ohtomo S, Nangaku M, Izuhara Y, Takizawa S, Strihou CY, Miyata T: **Cobalt ameliorates renal injury in an obese, hypertensive type 2 diabetes rat model.** *Nephrol Dial Transplant* 2008, **23**:1166–1172.
30. Soulis-Liparota T, Cooper M, Papazoglou D, Clarke B, Jerums G: **Retardation by aminoguanidine of development of albuminuria, mesangial expansion, and tissue fluorescence in streptozocin-induced diabetic rat.** *Diabetes* 1991, **40**:1328–1334.
31. Kawamura T, Huang CS, Peng X, Masutani K, Shigemura N, Billiar TR, Okumura M, Toyoda Y, Nakao A: **The effect of donor treatment with hydrogen on lung allograft function in rats.** *Surgery* 2011, **150**:240–249.
32. Itoh T, Hamada N, Terazawa R, Ito M, Ohno K, Ichihara M, Nozawa Y, Ito M: **Molecular hydrogen inhibits lipopolysaccharide/interferon  $\gamma$ -induced nitric oxide production through modulation of signal transduction in macrophages.** *Biochem Biophys Res Commun* 2011, **22**:143–149.
33. Friedman EA, Distant DA, Fleishacker JF, Boyd TA, Cartwright K: **Aminoguanidine prolongs survival in azotemic-induced diabetic rats.** *Am J Kidney Dis* 1997, **30**:253–259.
34. Bolton WK, Cattran DC, Williams ME, Adler SG, Appel GB, Cartwright K, Foiles PG, Freedman BI, Raskin P, Ratner RE, et al: **Randomized trial of an inhibitor of formation of advanced glycation end products in diabetic nephropathy.** *Am J Nephrol* 2004, **24**:32–40.
35. Tilton RG, Chang K, Hasan KS, Smith SR, Petrash JM, Misko TP, Moore WM, Currie MG, Corbett JA, McDaniel ML, et al: **Prevention of diabetic vascular dysfunction by guanidines. Inhibition of nitric oxide synthase versus advanced glycation end-product formation.** *Diabetes* 1993, **42**:221–232.
36. Suji G, Sivakami S: **DNA damage by free radical production by aminoguanidine.** *Ann N Y Acad Sci* 2006, **1067**:191–199.
37. Turgut F, Bolton WK: **Potential new therapeutic agents for diabetic kidney disease.** *Am J Kidney Dis* 2010, **55**:928–940.

doi:10.1186/2045-9912-2-18

**Cite this article as:** Katakura et al.: Hydrogen-rich water inhibits glucose and  $\alpha,\beta$ -dicarbonyl compound-induced reactive oxygen species production in the SHR.Cg-Lep<sup>FP</sup>/NDmcr rat kidney. *Medical Gas Research* 2012 **2**:18.

**Submit your next manuscript to BioMed Central and take full advantage of:**

- **Convenient online submission**
- **Thorough peer review**
- **No space constraints or color figure charges**
- **Immediate publication on acceptance**
- **Inclusion in PubMed, CAS, Scopus and Google Scholar**
- **Research which is freely available for redistribution**

Submit your manuscript at  
www.biomedcentral.com/submit

