Impact of O-GlcNAc on cardioprotection by remote ischaemic preconditioning in non-diabetic and diabetic patients

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Received 9 April 2012; revised 18 October 2012; accepted 6 November 2012; online publish-ahead-of-print 1 December 2012

Aims

Post-translational modification of proteins by O-linked β-N-acetylglucosamine (O-GlcNAc) is cardioprotective but its role in cardioprotection by remote ischaemic preconditioning (rIPC) and the reduced efficacy of rIPC in type 2 diabetes mellitus is unknown. In this study we achieved mechanistic insight into the remote stimulus mediating and the target organ response eliciting the cardioprotective effect by rIPC in non-diabetic and diabetic myocardium and the influence of O-GlcNAcylation.

Methods and results

The cardioprotective capacity and the influence on myocardial O-GlcNAc levels of plasma dialysate from eight healthy volunteers and eight type 2 diabetic patients drawn before and after subjection to an rIPC stimulus were tested on human isolated atrial trabeculae subjected to ischaemia/reperfusion injury. Dialysate from healthy volunteers exposed to rIPC improved post-ischaemic haemodynamic recovery (40 ± 6 vs. 16 ± 2%; P < 0.01) and increased myocardial O-GlcNAc levels. Similar observations were made with dialysate from diabetic patients before exposure to rIPC (43 ± 3 vs. 16 ± 2%; P < 0.001) but no additional cardioprotection or further increase in O-GlcNAc levels was achieved by perfusion with dialysate after exposure to rIPC (44 ± 4 and 42 ± 5 vs. 43 ± 3%; P = 0.7). The glutamine:fructose-6-phosphate amidotransferase (GFAT) inhibitor azaserine abolished the cardioprotective effects and the increment in myocardial O-GlcNAc levels afforded by plasma from diabetic patients and healthy volunteers treated with rIPC.

Conclusions

rIPC and diabetes mellitus per se influence myocardial O-GlcNAc levels through circulating humoral factors. O-GlcNAc signalling participates in mediating rIPC-induced cardioprotection and maintaining a state of inherent chronic activation of cardioprotection in diabetic myocardium, restricting it from further protection by rIPC.

Keywords

Diabetes mellitus type 2 • Ischaemia • Remote ischaemic preconditioning • Reperfusion injury • O-linked β-N-acetylglucosamine (O-GlcNAc)

1. Introduction

In addition to the accumulation of risk factors and more extensive vascular disease, a mechanism underlying the impaired prognosis and increased mortality in type 2 diabetes mellitus (DM) after acute myocardial infarction (AMI)1 may be increased susceptibility to ischaemia/reperfusion (IR) injury and reduced capacity for activation of endogenous cardioprotection. Activation may be achieved by conditioning strategies among which remote ischaemic preconditioning (rIPC)—a cardioprotective mechanism where repetitive sublethal episodes of ischaemia induce resistance to myocardial IR injury2,3—is most clinically applicable in AMI. However, cardioprotection by rIPC may be attenuated in diabetic myocardium.4–6 Conversely, diabetic animals may develop smaller infarct size after IR injury than non-diabetic animals,7,8 suggesting that diabetes per se activates basal innate metabolic cardioprotection without the ability to achieve further protection.
O-linked β-N-acetylglucosamine (O-GlcNAc) glycosylation is a novel post-translational modification of nuclear, cytoplasmic, and mitochondrial proteins that is sensitive to extracellular glucose concentrations. Elevated levels of O-GlcNAc have been associated with mediation of insulin resistance, atherosclerosis and cardiac dysfunction. O-GlcNAc levels are dynamically elevated in response to various stressors including local ischaemic preconditioning in non-diabetic myocardium. Notably, elevation of O-GlcNAc levels is cardioprotective, which may result from glycosylation of proteins such as voltage-dependent anion channel of the mitochondria (VDAC) and subsequent suppression of the mitochondrial permeability transition pore (mPTP). Exposure to high glucose and elevated expression of the O-GlcNAc transferase (OGT) increases mitochondrial protein O-GlcNAcylation and contributes to impaired mitochondrial function by compromising complex I, III, and IV activity and lower mitochondrial calcium and cellular ATP content. These are not only well-known abnormalities of the type 2 diabetic heart, but also components of the mechanisms underlying ischaemic preconditioning. We hypothesized that as a consequence of the possible inherent basal resistance to IR in type 2 diabetes, diabetes activates basal endogenous resistance to IR injury through up-regulation of O-GlcNAc levels and that cardioprotection by rIPC relies on O-GlcNAcylation, which cannot be further augmented because of its basal activation in diabetic patients.

RIPC liberates a dialyzable substance into the blood allowing protection to be transferred from a remotely preconditioned human donor to isolated perfused hearts. Using a dialysate of human plasma and isolated human atrial trabeculae and crossing between non-diabetic and diabetic donors and recipients, we were able to distinguish between non-diabetic and diabetic humoral responses of the effector organ and between non-diabetic and diabetic cellular effects in the target organ. The aim of this study was to achieve mechanistic insight into the remote stimulus mediating and the target organ response eliciting the cardioprotective effect by rIPC in non-diabetic and diabetic myocardium and the influence of O-GlcNAcylation.

2. Methods

A detailed description of the methods can be found in the Supplementary material online.

2.1 Remote ischaemic preconditioning protocol and preparation of dialysate

We recruited eight healthy volunteers and eight type 2 diabetic patients between 50 and 75 years of age. All the subjects underwent an oral glucose tolerance test, a physical examination, and an oral interview with a physician. Healthy volunteers with a fasting venous plasma glucose of ≥6.1 mmol/L or a venous plasma glucose of ≥7.8 mmol/L 2 h after oral glucose administration or with any sign of ischaemic heart disease or acute illness were excluded. All the type 2 diabetic patients had a fasting venous plasma glucose of ≥7.0 mmol/L and a 2 h venous plasma glucose of ≥11.1 mmol/L and when recruited for the study, HbA1c was between 6 and 9 mmol/L. Diabetic patients with any sign of ischaemic heart disease or acute illness were excluded from the study. Because of the influence of alcohol, caffeine, physical exercise, and antidiabetic medication on cardioprotection, all the subjects were instructed not to drink alcohol or caffeinated beverages and not to do physical exercise 5 days prior to examination. Diabetic patients were instructed not to take their oral antidiabetic drugs 4 days prior to examination and all other medicine including insulin on the day of examination.

The investigation conforms to the principles of the Declaration of Helsinki and the study protocol was approved by the regional Ethics Committee. Informed consent was obtained by the primary investigator.

The test persons were subjected to a remote ischaemic preconditioning stimulus of four times 5 min (rIPC) and four times 5 min + two times 10 min (intensified rIPC) upper arm ischaemia by inflation of a blood pressure cuff to 200 mmHg and 5 min reperfusion between inflations. Control blood samples of 120 mL were drawn from the cubital vein and collected in heparinized vials prior to the rIPC stimulus, and two rIPC blood samples were drawn after application of the two different intensities of the rIPC stimulus (Figure 1). Blood samples were centrifuged at 1520 g at 4°C for 20 min. Plasma was dialysed in 20-fold volume modified Krebs–Henseleit buffer ([pH 7.4] containing (in mmol/L) NaCl2 (118), KCl (4.8), NaHCO3 (27.2), MgCl2 (1.2), KH2PO4 (1.0) CaCl2 (2.0) and glucose (10)), using 12–14 kDa cut-off Spectra/Por Dialysis Membrane. Hence, six types of dialysate were prepared: (i) non-DM control dialysate; (ii) non-DM rIPC dialysate; (iii) non-DM intensified rIPC dialysate; (iv) DM control dialysate; (v) DM rIPC dialysate; and (vi) DM intensified rIPC dialysate.

2.2 Human atrial trabeculae

Atrial appendages were collected from patients undergoing elective heart surgery on extracorporeal circulation. Two study groups were included in the study by informed consent: non-diabetic patients and type 2 diabetic patients. Patients above the age of 85, patients with atrial fibrillation, and those with an ejection fraction of <30% or CKMB or Troponin T elevation within 2 weeks of surgery were excluded.

In connection with insertion of the venous cannula for extracorporeal circulation, right atrial appendages were collected. From these atrial appendages trabeculae were isolated and mounted in an organ bath with Krebs–Henseleit buffer as described in the Supplementary material online. Force of contraction was measured continuously via a force transducer and data acquired and analysed using the Notocord Hem evolutions software (Croissy sur Seine, France).

The atrial trabeculae were subjected to 75 min of stabilization, 30 min of superfusion with either control or rIPC dialysate depending on the experimental group, 90 min of simulated ischaemia, and 120 min of simulated reperfusion (Figure 1). Simulated ischaemia was induced by deoxygenating the buffer, replacing glucose and pyruvic acid with choline chloride, and increasing electrical stimulation from 1 to 3 Hz. At the end of reperfusion, trabeculae were snap-frozen in liquid nitrogen and stored at −80°C for western blotting and enzyme activity analysis for assessment of O-GlcNAc levels and formation. In three experimental groups, 80 μM azaeserin, an inhibitor of glutamine-fructose-6-phosphate amidotransferase (GFAT), was added to the superfusion buffer 15 min prior to superfusion with dialysate and was present throughout the rest of the experiment.

Non-diabetic and diabetic atrial trabeculae were randomized to experimental groups listed in Figure 1. Trabeculae that did not reach a force of contraction of 0.5 g by the end of the stabilization period were excluded. Recovery of contractile function expressed as a percentage of the baseline force of contraction is the primary endpoint. This was calculated by dividing the force of contraction reached at the end of reperfusion by the force of contraction at the end of the stabilization period for each trabecula.

2.3 O-GlcNAc analysis

Tissue samples were thawed in extraction buffer, ground with an electric grinder, sonicated for 2 × 10 s, and spun 18 000 g at 4°C for 30 min. Proteins were concentrated by ammonium sulfate precipitation (0–90%) on 100 μg of TCL, and samples were stored under desalting buffer for assays (below) or resuspended in 1× LDS containing dithiothreitol. Twenty micrograms of protein was loaded on two 8% PAGE gels and two 4–12% PAGE gels and western blotting was performed.
with primary antibodies: anti-O-GlcNAc antibody (CDT 110.6), anti-O-GlcNAc antibody (CTD 110.6) + 100 mM GlcNAc (Sigma), and anti-actin antibody (Sigma). Densitometry was calculated relative to densitometry of the corresponding Actin blot.

2.4 Hexosamine biosynthetic pathway enzyme activity analysis
Proteins were concentrated by ammonium sulfate precipitation (0–90%) from 150 çg of TCL and resuspended in Tris-HCL-buffer. O-GlcNAcase activity was estimated by measurement of the cleavage rate of a synthetic substrate p-nitrophenol N-acetylglucosamine. The activity assay was performed at 37°C for 24 h. Absorbance was measured at 400 nm. Activity is reported as picomoles of cleavage per min per mg of cell extract.

O-GlcNAc transferase activity was estimated as the rate of [H3]-UDP-N-acetyl-D-glucosamine (American Radiolabeled Chemicals, Inc., St Louis, MO, USA) transfer to an acceptor peptide, casein kinase II peptide. Reactions were performed at room temperature for 4 h and stopped by adding 50 mM formic acid. The reactions were purified over C18 cartridge (Phenomenex), eluted with methanol into scintillation fluid, and counted.

2.5 Statistical analysis
One-way ANOVA and Kruskal–Wallis tests with pairwise comparison by Bonferroni and Dunns post hoc tests when appropriate were used to assess differences between groups. Mann–Whitney and unpaired t-test were used to assess differences between DM control and DM control + azaserine. Data are presented as mean ± SEM, unless otherwise specified. A two-tailed P-value of <0.05 was considered statistically significant.

3. Results
3.1 Baseline characteristics
The characteristics of the test persons from whom dialysate was achieved and test persons from whom atrial trabeculae were obtained are shown in Table 1. All non-diabetic patients had fasting blood glucose <6.7 mmol/L, which was significantly lower than in diabetic patients.

3.2 Haemodynamic recovery of human atrial trabeculae
In the atrial trabeculae from non-diabetic patients, dialysate from non-diabetic volunteers undergoing rIPC significantly improved haemodynamic recovery compared with dialysate from non-diabetic without rIPC (control) (40 ± 6 vs. 16 ± 2%; P < 0.01; n = 7–8/group) (Figure 2A). No additional protection was observed by the intensified rIPC stimulus (39 ± 3%). Control dialysate from diabetic patients improved haemodynamic recovery compared with control dialysate from non-diabetic patients (43 ± 3 vs. 16 ± 2%; P < 0.001; n = 7–8/group) (Figure 2A). No further protection was acquired by rIPC or intensified rIPC dialysate from diabetic patients compared with control dialysate from diabetic patients (44 ± 4 and 42 ± 5 vs. 43 ± 3%; P = 0.7; n = 8/group). Azaserine abolished the cardioprotective effect of both rIPC dialysate and diabetic control dialysate while having no effect on non-diabetic control dialysate (n = 4–5/group) (Figure 4A and B).

In the atrial trabeculae from diabetic patients, we observed an improved recovery when perfused with non-diabetic and diabetic control dialysate compared with the non-diabetic atrial trabeculae (34 ± 4 and 35 ± 5 vs. 6 ± 2%; P < 0.05 for both comparisons). No additional protection was acquired by rIPC or perfusion with control dialysate from diabetic patients in diabetic trabeculae (Figure 2B).

Haemodynamic data presented in gram can be found in the Supplementary material online.
Mean force of contraction at baseline was 0.7 g (SEM ± 0.03 g). We found no difference in force of contraction at baseline between groups (P = 0.6).

### 3.3 Effect of remote ischaemic preconditioning on O-GlcNAc, OGT, and O-GlcNAcase levels

O-GlcNAc levels in the experimental groups are shown in Figures 2C and D, and 3, and 4C, and D. In non-diabetic atrial tissue rIPC dialysate from non-diabetic volunteers significantly augmented O-GlcNAc levels compared with control dialysate from non-diabetic volunteers (1.5 ± 0.15 vs. 1.0 ± 0.06, P < 0.05). Control and rIPC dialysate from diabetic patients significantly increased O-GlcNAc levels in non-diabetic atrial tissue compared with control dialysate from non-diabetic patients (P < 0.05 for both comparisons). Diabetic rIPC dialysate did not augment O-GlcNAc levels further compared with diabetic control dialysate (P = 0.35).

O-GlcNAc levels were increased in diabetic atrial tissue treated with control dialysate compared with non-diabetic atrial tissue treated with non-diabetic control dialysate (P = 0.02).

Azaserine blocked the increase in O-GlcNAc in non-diabetic atrial tissue treated with non-diabetic rIPC dialysate (Figures 4C and 5A). Azaserine also blocked the increase in O-GlcNAc in non-diabetic atrial tissue treated with diabetic control dialysate although not statistically significantly (Figures 4D and 5B).

### 3.4 O-GlcNAc transferase and O-GlcNAcase activity

OGT activity was increased by non-diabetic rIPC dialysate in non-diabetic atrial tissue (Figure 2E). The effect was abolished by azaserine (Figure 4E). No other dialysates affected OGT activity compared with non-diabetic control dialysate (Figures 2E and F, 4E and F).

Reduced O-GlcNAcase activity was seen in non-diabetic atrial tissue treated with non-diabetic rIPC dialysate, diabetic control, or diabetic rIPC dialysate compared with non-diabetic control dialysate (Figure 2G). O-GlcNAcase activity was also significantly reduced in all groups of diabetic atrial trabeculae compared with non-diabetic tissue treated with non-diabetic control dialysate (P < 0.01 for all comparisons) (Figure 2H). There was no additional reduction in O-GlcNAcase activity when comparing control dialysate with rIPC dialysate treatment in diabetic atrial tissue.

### 4. Discussion

The results of this study indicate that the mechanism underlying the cardioprotective effect of rIPC involves post-translational modification of myocardial proteins by O-GlcNAc, which is mediated by a circulating humoral factor independent of extracellular glucose concentration. Our results also demonstrate that type 2 diabetes per se reduces susceptibility to IR through a mechanism involving a humoral mediator that inherently up-regulates O-GlcNAcylation and restricts the potential for further protection from rIPC.

Table I Baseline characteristics of test persons

<table>
<thead>
<tr>
<th>Dialysate test persons</th>
<th>Non-diabetic (n = 8)</th>
<th>Diabetic (n = 8)</th>
<th>Atrial trabeculae patients</th>
<th>Non-diabetic (n = 25)</th>
<th>Diabetic (n = 14)</th>
</tr>
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<tbody>
<tr>
<td>Age, year (mean ± SD)</td>
<td>66 ± 6</td>
<td>63 ± 6</td>
<td>65 ± 12</td>
<td>70 ± 5</td>
<td></td>
</tr>
<tr>
<td>Male gender, n (%)</td>
<td>5 (60)</td>
<td>6 (80)</td>
<td>22 (88)</td>
<td>11 (79)</td>
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</tr>
<tr>
<td>IHD, n (%)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>19 (76)</td>
<td>13 (93)</td>
<td></td>
</tr>
<tr>
<td>EF, % (mean ± SD)</td>
<td>NA</td>
<td>NA</td>
<td>56 ± 7</td>
<td>53 ± 10</td>
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</tr>
<tr>
<td>Total cholesterol, mmol/L (mean ± SD)</td>
<td>5.2 ± 0.8</td>
<td>4.1 ± 0.6**</td>
<td>4.2 ± 0.9</td>
<td>3.9 ± 0.6</td>
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<tr>
<td>LDL, mmol/L (mean ± SD)</td>
<td>3.6 ± 0.6</td>
<td>2.0 ± 0.4**</td>
<td>2.3 ± 0.8</td>
<td>2.1 ± 0.4</td>
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<tr>
<td>HDL, mmol/L (mean ± SD)</td>
<td>1.2 ± 0.2</td>
<td>1.5 ± 0.5</td>
<td>1.3 ± 0.3</td>
<td>1.2 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>Triglyceride, mmol/L (mean ± SD)</td>
<td>1.1 ± 0.4</td>
<td>1.2 ± 0.6</td>
<td>1.4 ± 0.5</td>
<td>1.3 ± 0.4</td>
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<tr>
<td>Statin therapy, n (%)</td>
<td>0 (0)</td>
<td>6 (75)**</td>
<td>20 (80)</td>
<td>13 (93)</td>
<td></td>
</tr>
<tr>
<td>Antihypertensive therapy, n (%)</td>
<td>0 (0)</td>
<td>5 (63)*</td>
<td>21 (84)</td>
<td>14 (100)</td>
<td></td>
</tr>
<tr>
<td>Fasting blood glucose, mmol/L (mean ± SD)</td>
<td>5.3 ± 0.9</td>
<td>9.4 ± 2.8**</td>
<td>5.7 ± 0.4</td>
<td>7.4 ± 1.4***</td>
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<tr>
<td>HbA1c, mmol/L (mean ± SD)</td>
<td>0.077 ± 0.01</td>
<td>0.066 ± 0.01</td>
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<tr>
<td>Years with DM, year (mean ± SD)</td>
<td>9.9 ± 5.8</td>
<td>10.4 ± 6.0</td>
<td></td>
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<tr>
<td>&lt;10 years with DM, n (%)</td>
<td>3 (37)</td>
<td>6 (46)</td>
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<tr>
<td>≥10 years with DM, n (%)</td>
<td>5 (63)</td>
<td>7 (54)</td>
<td></td>
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<tr>
<td>Metformine therapy, n (%)</td>
<td>4 (50)</td>
<td>10 (71)</td>
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<tr>
<td>Insulin therapy, n (%)</td>
<td>6 (75)</td>
<td>6 (43)</td>
<td></td>
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<tr>
<td>Neuropathy, n (%)</td>
<td>5 (63)</td>
<td>1 (7)</td>
<td></td>
<td></td>
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<tr>
<td>Retinopathy, n (%)</td>
<td>2 (25)</td>
<td>1 (7)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

IHD, ischaemic heart disease; EF, ejection fraction; LDH, low-density lipoprotein; HDL, high-density lipoprotein.

*p < 0.05.

**p < 0.01.

***p < 0.001.

****p < 0.0001 compared with respective non-diabetic subjects.
Figure 2 (A and B) Recovery of contractile force in atrial trabeculae from non-diabetic (A) and diabetic (B) patients. (A) No difference between diabetic control and diabetic rIPC dialysate. (B) No difference between any groups. (C and D) O-GlcNAc levels in atrial trabeculae from non-diabetic (C) and diabetic (D) patients. (C) No difference between diabetic control and diabetic rIPC dialysate. (D) No difference between any groups. (E and F) OGT activity in atrial trabeculae from non-diabetic (E) and diabetic (F) patients. (E) No difference between diabetic control and diabetic rIPC dialysate. (F) No difference between any groups. (G and H) O-GlcNAcase activity in atrial trabeculae from non-diabetic and diabetic patients. (G) No difference between diabetic control and diabetic rIPC dialysate. (H) No difference between any groups. Data are mean ± SEM.
In this study we extended our previous model of ‘cross-species’ transfer of cardioprotective factors released by rIPC from a human-to-rabbit model to a human-to-human model. Using isolated human atrial trabeculae and crossing dialysate between effector and target organs from different individuals, we took advantage of the possibility of differentiating the mechanisms behind non-diabetic and diabetic humoral responses of the effector organ and the mechanisms behind non-diabetic and diabetic cellular effects in the target organ.

Similar to local ischaemic preconditioning, rIPC did not confer improved haemodynamic recovery by transfer of dialysate from either non-diabetic or diabetic donors. In contrast to an intensified local ischaemic preconditioning stimulus, which may elicit cardioprotection, we did not find a similar improvement by an intensified rIPC stimulus. This may be due to differences in the inherent mechanisms of local preconditioning and rIPC and it cannot be ruled out that our intensified rIPC stimulus was insufficient.

Our study provides further knowledge about the mechanism behind the absence of effect of rIPC in human diabetic myocardial tissue, because dialysate from diabetic patients even before exposure to rIPC improved post-ischaemic haemodynamic recovery in non-diabetic atrial trabeculae. Similarly, diabetic atrial trabeculae perfused with control dialysate enhanced post-ischaemic haemodynamic recovery compared with non-diabetic trabeculae. However, as post-ischaemic functional recovery of the chronically cardioprotected diabetic trabeculae is similar to recovery of non-diabetic trabeculae treated with rIPC or dialysate from diabetic patients, our findings suggest that a basal potential of the end effector of cardioprotection is present in diabetic hearts. However, this potential is fully utilized and not accessible for further activation. As a consequence, type 2 DM per se induces a state of inherent basal resistance to IR by release of a circulating humoral factor, which also restricts the potential for further protection by rIPC.

Even though resistance to IR injury may be increased in type 2 diabetes, the drawback appears to be that the potential for further organ protection by rIPC is compromised. Our results appear to provide an explanation for this by our demonstration of the involvement of O-GlcNAc in cardioprotection.

Diabetic animal models are characterized by increased myocardial O-GlcNAc level. Consistent with these observations, O-GlcNAc levels were elevated in our human atrial tissue samples from diabetic patients subjected to IR injury. This increment was induced by a circulating humoral factor as demonstrated by the fact that non-diabetic atrial tissue perfused with dialysate from diabetic patients not exposed to rIPC also increased myocardial O-GlcNAc levels. Like the cardioprotective effect of dialysate from diabetic patients, the elevation of O-GlcNAc levels was blocked by azaserine, suggesting that the cardioprotective effect of diabetes is related to a similar humoral factor and mediated by O-GlcNAc. Azaserine is a commonly used GFAT inhibitor used to block an increase in O-GlcNAc levels and cardioprotection in vitro with the same concentration as used in our studies. However, azaserine may have other cellular actions moderating its specificity. Even though the reduction of O-GlcNAc levels in the diabetic control group did not reach statistical significance, we consider this limitation mainly related to the restricted number of patients.

Cardioprotection by rIPC was associated with increased myocardial O-GlcNAc levels. A mechanistic connection between cardioprotection by rIPC and myocardial O-GlcNAc levels is substantiated by our finding that the absence of the capability to further augment O-GlcNAc levels by rIPC is associated with reduced efficacy of rIPC in diabetic patients. The cardioprotective effect of dialysate from diabetic patients in non-diabetic trabeculae implies that diabetic patients are capable of triggering a state of cardioprotection.

Like the inherent diabetic cardioprotection, perfusion with the GFAT inhibitor azaserine abolished the cardioprotective effects and the elevation of O-GlcNAc levels, demonstrating that cardioprotection by rIPC is dependent on augmentation of O-GlcNAc. Similarly, Jones et al. demonstrated that ischaemic preconditioning enhances O-GlcNAc levels in vivo and reduces sensitivity to mPTP formation. There are several potential mechanistic links between O-GlcNAc modification and cardioprotection. Exposure of cardiomyocytes to the O-GlcNAcase inhibitor O-(2-acetamido-2-deoxy-D-glucopyranosylidene) amino-N-phenylcarbamate (PUGNAc) causes O-GlcNAc modification of VDAC, which is a central element in formation of mPTP, and make them resistant to induction of mPTP and death. Augmentation of O-GlcNAc attenuates cell injury following IR by inhibiting the opening of mPTP and reducing Ca^{2+} overload and ROS.
Figure 4 (A and B) The effect of perfusion with the GFAT inhibitor azaserine on the recovery of contractile force in atrial trabeculae from non-diabetic patients, when treated with non-diabetic dialysate (A) and diabetic dialysate (B). (A) No difference in recovery between control + azaserine and rIPC + azaserine. Non-diabetic control and non-diabetic rIPC same data as in Figure 2A. (B) Diabetic control same data as in Figure 2B. (C and D) O-GlcNAc levels in atrial trabeculae from non-diabetic patients, when treated with non-diabetic dialysate (C) and diabetic dialysate (D). (C) No difference in recovery between control + azaserine and rIPC + azaserine. Non-diabetic control and non-diabetic rIPC same data as in Figure 2C. (D) Difference between diabetic control and diabetic control + azaserine not significant $P = 0.10$. Diabetic control same data as in Figure 2D. (E and F) OGT activity in atrial trabeculae from non-diabetic patients, when treated with non-diabetic dialysate (E) and diabetic dialysate (F). (E) No difference in recovery between control + azaserine and rIPC + azaserine. Non-diabetic control and non-diabetic rIPC same data as in Figure 2E. (F) No difference between diabetic control and diabetic control + azaserine. Diabetic control same data as in Figure 2F. Data are mean ± SEM.
It is unlikely that these transmitters are transferred in the plasma dialysate because of their short half-life and size. Agents more likely stimulate neural release of other transmitters, but the precise signal transduction pathway from the rIPC stimulus to O-GlcNAcylation and prevention of mPTP opening is unknown.

O-GlcNAc modification is regulated in a glucose-dependent manner and may provide a mechanistic explanation to the finding that type 2 DM modifies signalling pathways responsible for cardioprotection through chronic metabolic influence primarily by hyperglycaemia. Indeed, a difference in plasma glucose was present between non-diabetic volunteers and diabetic patients during the rIPC stimulus and collection of blood for dialysate. However, after dialyzation glucose concentrations were identical in all dialysates, indicating that the humoral cardioprotective factor in diabetic plasma that simultaneously increases myocardial O-GlcNAc levels acutely after IR injury is not glucose. In addition to extracellular glucose concentration, O-GlcNAcylation is sensitive to circulating glutamine concentrations because glucose and an amine group from glutamine converted into glutamate enter the hexosamine biosynthesis pathway to UDP-GlcNAc. Glutamine mediates cardioprotection through O-GlcNAcylation also in DM. Although cardioprotection is induced by glutamine, efficacy is dependent on circulating glucose concentrations, indicating that an increase in myocardial glucose uptake by IPC may boost the flux through hexosamine biosynthetic pathway to increase O-GlcNAc levels.

Circulating humoral factor(s) mediating cardioprotection by rIPC and type 2 diabetes may share mechanistic elements but do not appear to be completely identical. We identified a difference in the mechanism behind elevation of O-GlcNAc level by diabetes and rIPC. Plasma from non-diabetic patients subjected to rIPC caused an increase in OGT activity and a decrease in O-GlcNAcase activity, whereas elevation in O-GlcNAc level and cardioprotection by diabetes was characterized by a reduction in O-GlcNAcase activity only. Only limited knowledge of the rearrangement in the O-GlcNAc network in human diabetes is available. In most animal studies, expression of OGT is elevated, whereas expression of O-GlcNAcase is reduced. Our results are in accordance with the finding that O-GlcNAcase expression is reduced in type 2 diabetes with progression of the disease. In contrast, an acute stress signal like rIPC activates not only OGT, but also reduces O-GlcNAcase activity to increase O-GlcNAc levels in the heart.

We have previously demonstrated that diabetic peripheral neuropathy influences the release of the transferable cardioprotective factors in diabetic patients. In the study in question, five of the diabetic patients undergoing preconditioning and only one patient from whom atrial tissue was obtained had neuropathy. Despite this limitation, we were able to demonstrate that diabetes per se activates cardioprotection through augmentation of O-GlcNAc in contrast to our findings in the present human-to-human transfer, our human-to-rabbit transfer only conferred cardioprotection after preconditioning and not by non-conditioned diabetic dialysate. This difference may reflect species-specific differences in the target organ.

A limitation of the study in question is that atrial trabeculae may not reflect the metabolism and physiology of ventricular myocardium. Nevertheless, important similarities between atrial and ventricular were demonstrated. Antidiabetic medication and caffeine have known cardioprotective effects. Diabetic patients were restricted from taking these agents prior to the rIPC stimulus and collection of blood samples and therefore did not confound the result.
Impact of O-GlcNAc on cardioprotection

In conclusion, this study demonstrates that the cardioprotective effects of rIPC are connected to augmentation of O-GlcNAc levels in humans. Furthermore, type 2 DM per se increases myocardial O-GlcNAc levels and induces a state of inherent chronic cardioprotection, which restricts the potential for further organ protection by rIPC in diabetic patients. The mechanisms seem to differ as rIPC increases O-GlcNAc levels by increasing OGT activity and decreasing O-GlcNacase activity, while diabetes mellitus decreases only O-GlcNacase activity.

Supplementary material

Supplementary material is available at Cardiovascular Research online.

Acknowledgements

We greatly appreciate the technical assistance from Russell A. Reeves, Anja Helveg Larsen, and Casper Elkjær.

Conflict of interest: none declared.

Funding

This work was supported by Leducq (CVD 06), the Danish Research Council (11-115818), American Heart Association (SD090162N to N.E.Z.), and the National Heart Lung and Blood Institute (R21-HL-108003 and PO1-HL107153 to N.E.Z.).

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