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Annexin A1 attenuates microvascular complications through restoration of Akt signalling in a murine model of type 1 diabetes

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Abstract

Aims/hypothesis Microvascular complications in the heart and kidney are strongly associated with an overall rise in inflammation. Annexin A1 (ANXA1) is an endogenous anti-inflammatory molecule that limits and resolves inflammation. In this study, we have used a bedside to bench approach to investigate: (1) ANXA1 levels in individuals with type 1 diabetes; (2) the role of endogenous ANXA1 in nephropathy and cardiomyopathy in experimental type 1 diabetes; and (3) whether treatment with human recombinant ANXA1 attenuates nephropathy and cardiomyopathy in a murine model of type 1 diabetes.

Methods ANXA1 was measured in plasma from individuals with type 1 diabetes with or without nephropathy and healthy

donors. Experimental type 1 diabetes was induced in mice by injection of streptozotocin (STZ; 45 mg/kg i.v. per day for 5 consecutive days) in C57BL/6 or *Anxa1*^{-/-} mice. Diabetic mice were treated with human recombinant (hr)ANXA1 (1 µg, 100 µl, 50 mmol/l HEPES; 140 mmol/l NaCl; pH 7.4, i.p.) or vehicle (100 µl, 50 mmol/l HEPES; 140 mmol/l NaCl; pH 7.4, i.p.).

Results Plasma levels of ANXA1 were elevated in individuals with type 1 diabetes with/without nephropathy compared with healthy individuals (66.0 ± 4.2/64.0 ± 4 ng/ml vs 35.9 ± 2.3 ng/ml; *p* < 0.05). Compared with diabetic wild-type (WT) mice, diabetic *Anxa1*^{-/-} mice exhibited a worse diabetic phenotype and developed more severe cardiac (ejection fraction; 76.1 ± 1.6% vs 49.9 ± 0.9%) and renal dysfunction (proteinuria; 89.3 ± 5.0 µg/mg vs 113.3 ± 5.5 µg/mg). Mechanistically, compared with non-diabetic WT mice, the degree of the phosphorylation of mitogen-activated protein kinases (MAPKs) p38, c-Jun N-terminal kinase (JNK) and extracellular signal-regulated kinase (ERK) was significantly higher in non-diabetic *Anxa1*^{-/-} mice in both the heart and kidney, and was further enhanced after STZ-induced type 1 diabetes. Prophylactic treatment with hrANXA1 (weeks 1–13) attenuated both cardiac (ejection fraction; 54.0 ± 1.6% vs 72.4 ± 1.0%) and renal (proteinuria; 89.3 ± 5.0 µg/mg vs 53.1 ± 3.4 µg/mg) dysfunction associated with STZ-induced diabetes, while therapeutic administration of hrANXA1 (weeks 8–13), after significant cardiac and renal dysfunction had already developed, halted the further functional decline in cardiac and renal function seen in diabetic mice administered vehicle. In addition, administration of hrANXA1 attenuated the increase in phosphorylation of p38, JNK and ERK, and restored phosphorylation of Akt in diabetic mice.

Conclusions/interpretation Overall, these results demonstrate that ANXA1 plasma levels are elevated in individuals with

Christoph Thiemermann and Egle Solito contributed equally to this work.

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type 1 diabetes independent of a significant impairment in renal function. Furthermore, in mouse models with STZ-induced type 1 diabetes, ANXA1 protects against cardiac and renal dysfunction by returning MAPK signalling to baseline and activating pro-survival pathways (Akt). We propose ANXA1 to be a potential therapeutic option for the control of comorbidities in type 1 diabetes.

Keywords Akt · Annexin A1 · Diabetes · Diabetic cardiomyopathy · Diabetic nephropathy · MAPK · Microvascular complications · Type 1 diabetes

Abbreviations

| | |
|-------|---------------------------------------|
| ACR | Albumin-to-creatinine ratio |
| ANXA1 | Annexin A1 |
| CRP | C-reactive protein |
| EF | Ejection fraction |
| ERK | Extracellular signal-regulated kinase |
| FAC | Fractional area change |
| FPR2 | Formyl peptide receptor 2 |
| FS | Fractional shortening |
| Hr | Human recombinant |
| JNK | c-Jun N-terminal kinase |
| MAPK | Mitogen-activated protein kinase |
| PCT | Proximal convoluted tubules |
| PI3K | Phosphoinositide-3 kinase |
| STZ | Streptozotocin |
| WT | Wild-type |

Introduction

Type 1 diabetes is an autoimmune disease often diagnosed in childhood that is characterised by the loss of insulin producing beta cells, which leads to hyperglycaemia [1]. Even with strict glycaemic control using rigorous insulin management, microvascular complications including diabetic nephropathy [2] and diabetic cardiomyopathy [3] develop over time. The microvascular complications associated with diabetes are key drivers of morbidity (and ultimately mortality) rates, and therefore put a significant economic burden on healthcare providers. Most notably, there are no specific therapeutic interventions that prevent, delay or reduce the microvascular complications associated with diabetes. Diabetic nephropathy is the primary cause of death in 21% of people with type 1 diabetes [4], and cardiovascular disease, which includes diabetic cardiomyopathy, accounts for 44% of all fatalities in type 1 diabetes [5]. Both pathologies are characterised by an impairment in function (kidney [proteinuria [6]], heart [impairment in systolic contractility [7]]) caused by local

inflammation [8], endothelial dysfunction [9] and loss of survival pathways, the latter of which predisposes tissues to injury.

Resolution of inflammation and modulation of survival pathways are critical to normal physiology and are often altered in disease states. Annexin A1 (ANXA1) is a 37 kDa member of the multigene annexin family with anti-inflammatory and pro-resolving activities [10]. The N-terminus of each family member varies giving each its unique functionality [11]. ANXA1 binds formyl peptide receptor 2 (FPR2/ALX), downregulating the production of proinflammatory processes but activating pro-survival pathways via protein kinase C [12]. ANXA1 levels are modulated in many disease states including cancer [13], multiple sclerosis [14], cystic fibrosis [15] and obesity/the metabolic syndrome [16]. Human recombinant ANXA1 (hrANXA1) or its N-terminal peptide (Ac2-26) have therapeutic benefits in many experimental models of disease, including rheumatoid arthritis [17], atherosclerosis [18] and nonalcoholic steatohepatitis [19].

The role of ANXA1 as a pro-resolving-like molecule in type 1 diabetes is unknown. Therefore, this study was designed to investigate: (1) the plasma levels of ANXA1 in individuals with diabetes with/without nephropathy; (2) the role of endogenous ANXA1 in an animal model of type 1 diabetes and in the subsequent development of microvascular complications (diabetic cardiomyopathy and diabetic nephropathy); (3) if prophylactic daily administration with hrANXA1 prevents diabetic cardiomyopathy and/or nephropathy; and (4) if therapeutic intervention with hrANXA1 (after microvascular complications have developed) can halt the progression of diabetic cardiomyopathy and/or nephropathy.

Methods

Use of human participants: ethics statement The study was approved by the research ethics committee and was undertaken in adherence to the Declaration of Helsinki. All participants gave written informed consent. Participants with type 1 diabetes were recruited from the diabetes outpatient clinic of Guy's and St Thomas Hospitals (London, UK). Healthy donors were recruited from the William Harvey Research Institute (London, UK) and both covered by ethical approval. Non-fasting plasma was obtained from participants with type 1 diabetes with or without a diagnosis of diabetic nephropathy and healthy donors.

Use of experimental animals: ethics statement The animal protocols followed in this study were approved by the Animal Welfare Ethics Review Board (AWERB) of Queen Mary University of London in accordance with the derivatives of both the Home Office guidance on the Operation of Animals (Scientific Procedures Act 1986) published by Her Majesty's

Stationery Office and the Guide for the Care and Use of Laboratory Animals of the National Research Council. This study was performed under licence issued by the Home Office (Procedure Project Licence; 70/8350) (see the electronic supplementary material [ESM] [Methods](#) for further details).

Human study population Details on the study population are provided in the ESM [Methods](#) and ESM Table 1. The population included healthy volunteers ($n = 20$), participants with type 1 diabetes ($n = 20$) and participants with type 1 diabetes and nephropathy ($n = 22$). Plasma ANXA1 and C-reactive protein (CRP) was measured using standard ELISA (described below). Correlation studies were carried out between plasma ANXA1, plasma CRP and BMI.

Animal model of diabetes Experimental diabetes was induced in 10-week-old wild-type (WT) male C57BL/6 or *Anxa1*^{-/-} mice (*Anxa1*^{tm1Rj} on a C57BL/6 background) (Charles River Laboratories, Margate, UK). Diabetes was induced using streptozotocin (STZ; 45 mg/kg i.p. in 0.9 mol/l citrate buffer, 5 days, $n = 8$), while sham mice received vehicle only (10 ml/kg, 0.9 mol/l citrate buffer i.p., 5 days, $n = 8$). hrANXA1 was produced and purified as previously published [18]. Treatment groups received either prophylactic treatment (weeks 1–13 after STZ administration, $n = 6$), treatment during STZ administration (days 1–5, $n = 6$) or therapeutic treatment (weeks 8–13 after STZ administration, $n = 6$) with hrANXA1 (1 µg, 100 µl, 50 mmol/l HEPES; 140 mmol/l NaCl; pH 7.4, i.p.) from weeks 1–13 or vehicle. The study has been repeated in two independent experiments each time animals were randomly assigned a treatment group and all analysis of in vivo function was assessed in a blinded fashion.

OGTT Mice were fasted for 18 h prior to testing, given an oral bolus of glucose (1 g/kg in H₂O p.o.) and blood glucose was measured at time 0 and then at 15 min intervals for 120 min by tail vein puncture.

Assessment of cardiac function in vivo Cardiac function was assessed in mice by echocardiography in vivo as previously described [20]. Briefly, at either 7 or 13 weeks after STZ or vehicle administration, anaesthesia was induced and two-dimensional B-mode and M-mode echocardiography images were recorded using a Vevo-770 imaging system (VisualSonics, Toronto, ON, Canada).

Blood and biochemical analysis Urea, creatinine and sodium were measured by a commercial veterinary testing laboratory (IDEXX, Wetherby, UK); serum insulin and urine albumin were measured using commercially available ELISA kits (Abcam, Cambridge, UK and Bethyl Laboratories, Montgomery, TX, USA).

ELISA for ANXA1 Concentrations of ANXA1 in human plasma, mouse serum or protein lysates from heart and kidney were measured by ELISA as previously reported [21–23] (see ESM [Methods](#) for further details).

Histological analysis Kidneys were fixed in 10% neutral-buffered formalin for 48 h before being dehydrated with 70% ethanol. Tissues were embedded in paraffin and 4 µm sections were cut. Tissue was either stained with periodic acid–Schiff's (PAS; Sigma, St Louis, MO, USA) or Sirius Red (Abcam) as previously described [24] (see ESM [Methods](#) for further details).

Western blot analysis The degree of phosphorylation of Ser⁴⁷³ on Akt/p-Akt (Cell Signaling Technology, Danvers, MA, USA), Thr¹⁸⁰/Tyr¹⁸² on p38/p-p38 (New England Biolabs, Ipswich, MA, USA), Thr¹⁸³/Tyr¹⁸⁵ on c-Jun N-terminal kinase (JNK)/p-JNK (Abcam) and Thr²⁰²/Tyr²⁰⁴ on extracellular signal-regulated kinase (ERK1/2)/p-ERK1/2 (New England Biolabs) was measured by semi-quantitative western blot analyses in mouse heart and kidney tissue as described previously [20, 25] (see ESM [Methods](#) for further details).

Statistical analysis All data in the text and figures are presented as mean and SEM of n observations, where n represents the number of animals studied. All statistical analysis was calculated using GraphPad Prism 6 (GraphPad Software, San Diego, CA, USA). Data without repeated measurements were assessed by a one-way ANOVA followed by Bonferroni post hoc test (multiple comparison) or unpaired Student's t test where appropriate. OGTTs were analysed using the area under the receiver operating characteristic (ROC) curve. A p value of <0.05 was considered to be statistically significant.

Results

Participants with type 1 diabetes have elevated ANXA1 plasma levels Figure 1a shows plasma concentration of ANXA1 in healthy donors and in participants with diabetes with/without nephropathy. The median age and sex distribution of the three test groups was similar (ESM Table 1). Plasma levels of ANXA1 were higher in individuals with diabetes with or without a diagnosis of diabetic nephropathy compared with healthy individuals (Fig. 1a), with no observed sex difference in ANXA1 concentration (ESM Fig. 1). Participants with diabetic nephropathy have higher plasma levels of CRP (a marker of systemic inflammation) compared with those with no nephropathy (Fig. 1b). However, we found no significant positive correlation between CRP and ANXA1 or BMI and ANXA1 (ESM Fig. 2a, b), but there was a strong positive correlation between plasma CRP and BMI (ESM Fig. 2c).

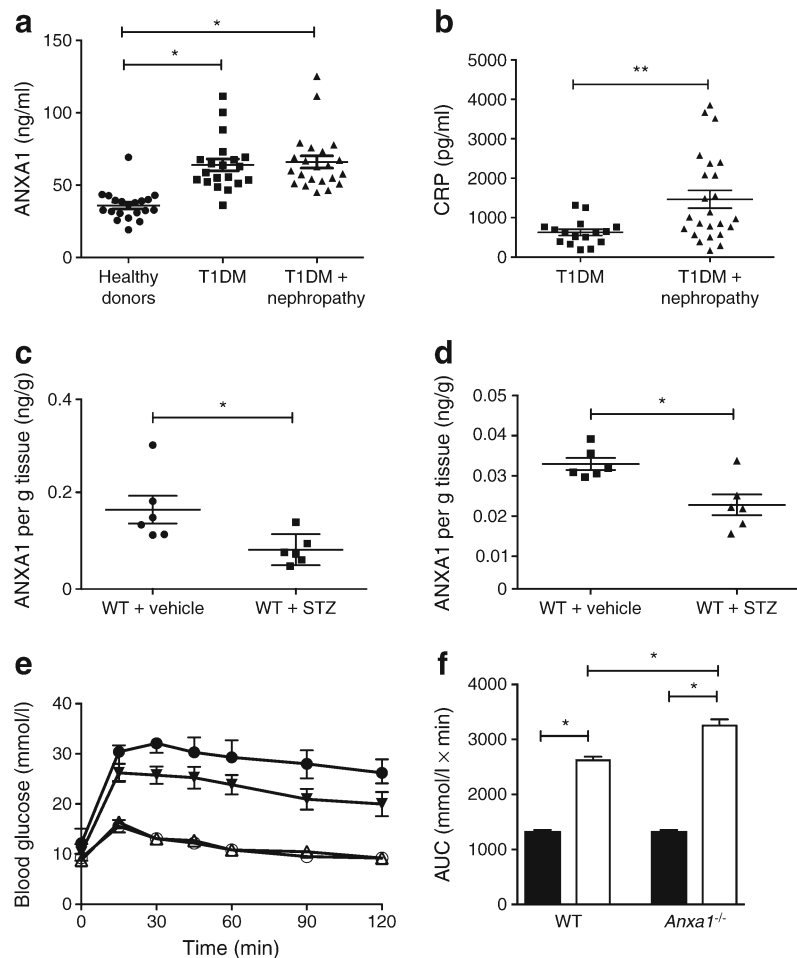


Fig. 1 (a) ANXA1 levels were measured by sandwich ELISA in the plasma of healthy donors ($n = 20$), participants with type 1 diabetes (T1DM) without diabetic nephropathy ($n = 20$) and participants with type 1 diabetes with diabetic nephropathy ($n = 22$). (b) CRP was measured in plasma of participants with type 1 diabetes with and without diabetic nephropathy. (c, d) ANXA1 levels were measured by sandwich ELISA in mice at week 13 after STZ-induced diabetes in serum in tissue lysates from (c) the heart and (d) the kidney. (e) An OGTT was performed at week 13. Experimental groups: WT + vehicle (100 μ l, 0.1 mol/l citrate

buffer, i.p. for 5 days; white triangles), WT + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days; black triangles), *Anxa1*^{-/-} + vehicle (100 μ l, 0.1 mol/l citrate buffer, i.p. for 5 days; white circles) and *Anxa1*^{-/-} + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days; black circles). (f) AUC of the OGTT. Black bars, vehicle; white bars, STZ. Data analysed by a Student's *t* test (b–d) or by one-way ANOVA followed by a Bonferroni post hoc test (a, f), and expressed as mean \pm SEM. $n = 6$ –8 per group. * $p < 0.05$, ** $p < 0.01$

Diabetic *Anxa1*^{-/-} mice have a more severe diabetic phenotype as a result of STZ-induced type 1 diabetes Using a reverse translational approach, from humans to rodents, we wanted to understand the biological effect of modulating endogenous ANXA1 levels in a mouse model of type 1 diabetes in both WT and *Anxa1*^{-/-} mice. When compared with non-diabetic mice, diabetic mice demonstrated a significant decrease in ANXA1 levels in both the heart and kidney (Fig. 1c, d), while secreted ANXA1 levels in the serum were unchanged (Table 1). Diabetic WT and *Anxa1*^{-/-} mice had depleted serum insulin levels, resulting in elevated non-fasted blood glucose levels (Table 1). Interestingly, diabetic *Anxa1*^{-/-} mice had significantly increased non-fasted blood glucose (Table 1) and a more severe impairment of OGTT compared with diabetic WT

mice, suggesting *Anxa1*^{-/-} mice have a more severe diabetic phenotype (Fig. 1e, f).

Diabetic *Anxa1*^{-/-} mice have more severe cardiac dysfunction as a result of STZ-induced type 1 diabetes Next, we assessed the role of endogenous ANXA1 on cardiac dysfunction associated with STZ-induced diabetes using echocardiography. When compared with non-diabetic WT mice, diabetic WT mice demonstrated a significant reduction in ejection fraction (EF) (Fig. 2a and ESM Fig. 3b), fractional shortening (FS) (Fig. 2b and ESM Fig. 3b) and fractional area change (FAC) (Fig. 2c). This indicates the development of systolic cardiac dysfunction, with even further deterioration in EF, FS and FAC observed in diabetic *Anxa1*^{-/-} mice (Fig. 2a–c and ESM Fig. 3d). Diabetic WT and *Anxa1*^{-/-} mice both

Table 1 Effects of endogenous ANXA1 and administered hrANXA1 on metabolic parameters in STZ-induced diabetes

| | WT+veh | WT+STZ | <i>Anxa1</i> ^{-/-} +veh | <i>Anxa1</i> ^{-/-} +STZ | Sham | STZ+veh | STZ+hrANXA1 weeks 1–13 | STZ+hrANXA1 days 1–5 | STZ+hrANXA1 weeks 8–13 |
|-----------------------------------|--------------|---------------|----------------------------------|----------------------------------|---------------------------|--------------|------------------------|----------------------|------------------------|
| Weight (g) | 32.52 ± 1.00 | 27.13 ± 0.51* | 31.82 ± 0.62 | 23.50 ± 0.62 [‡] | 31.83 ± 0.83 [†] | 26.67 ± 0.33 | 26.67 ± 0.33 | 27.33 ± 1.09 | 25.00 ± 0.82 |
| Heart rate (bpm) | 521 ± 1 | 503 ± 3 | 504 ± 8 | 504 ± 8.4 | 513 ± 6 | 493 ± 11 | 507 ± 3 | 488 ± 5 | 497 ± 6 |
| Insulin (pmol/l) | 1375 ± 256 | 493 ± 39* | 1576 ± 493 | 420 ± 100 [‡] | 1736 ± 39 [†] | 576 ± 19 | 493 ± 19 | 479 ± 39 | 534 ± 39 |
| Non-fasted blood glucose (mmol/l) | 7.86 ± 0.89 | 15.30 ± 0.21* | 7.82 ± 19.33 | 19.33 ± 1.18 [‡] | 7.42 ± 0.65 [†] | 18.47 ± 1.19 | 15.76 ± 1.30 | 17.22 ± 1.69 | 16.08 ± 1.91 |
| OGTT (mmol/l × min) | 1342 ± 78 | 2638 ± 47* | 1287 ± 54 | 3273 ± 93 [‡] | 1404 ± 32 [†] | 2695 ± 210 | 2502 ± 129 | 2607 ± 100 | 2404 ± 133 |
| Serum ANXA1 (ng/ml) | 1.35 ± 0.15 | 1.96 ± 0.13 | n/a | n/a | n/a | n/a | n/a | n/a | n/a |

Data expressed as mean ± SEM; *n* = 6–8 per group

Body weight, heart rate, insulin level, non-fasted blood glucose, OGTT and serum ANXA1 were assessed 13 weeks after STZ induction of type 1 diabetes

Experimental groups in study one: WT + vehicle (100 µl, 0.1 mol/l citrate buffer, i.p. for 5 days), WT + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days), *Anxa1*^{-/-} + vehicle (100 µl, 0.1 mol/l citrate buffer, i.p. for 5 days) and *Anxa1*^{-/-} + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days); in study two: sham (no STZ), WT + vehicle, STZ + hrANXA1 weeks 1–13 (1 µg hrANXA1, i.p. daily weeks 1–13), STZ + hrANXA1 days 1–5 (RED1 µg hrANXA1, i.p. daily days 1–5), and STZ + hrANXA1 weeks 8–13 (1 µg hrANXA1, i.p. daily weeks 8–13)

Data analysed by a one-way ANOVA followed by a Bonferroni post hoc test

**p* < 0.05 vs WT+veh, [‡]*p* < 0.05 vs *Anxa1*^{-/-}+veh, [†]*p* < 0.05 vs STZ+veh

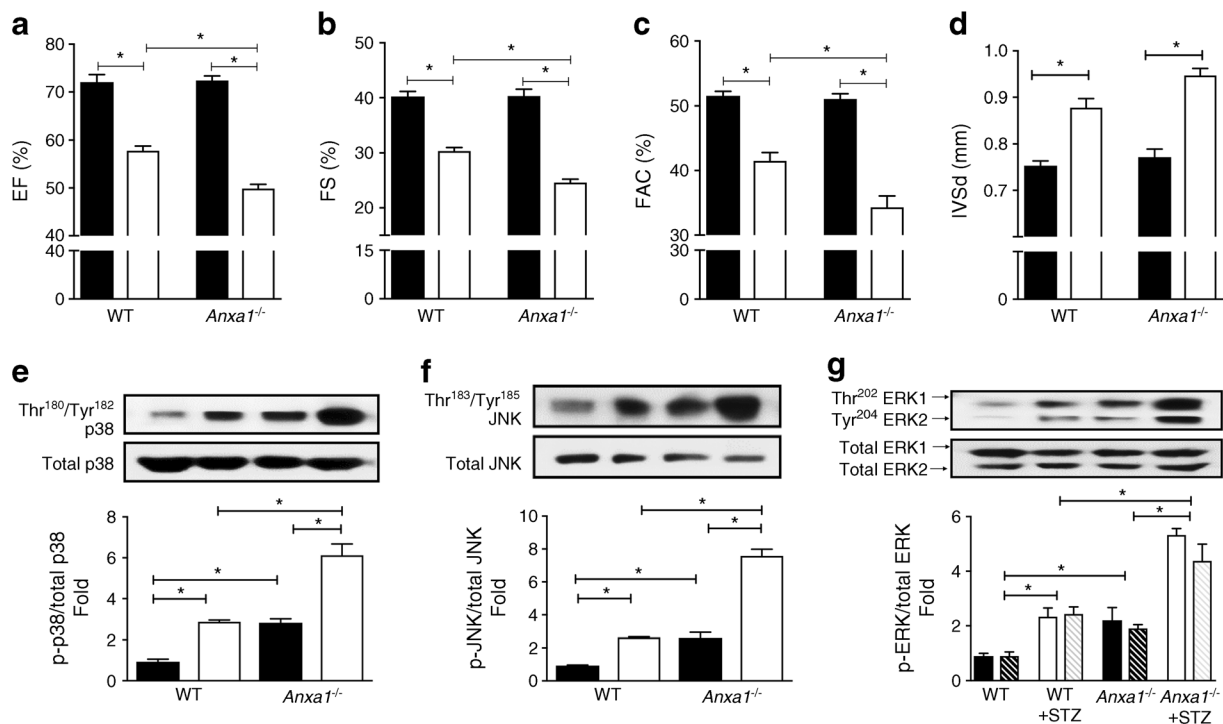


Fig. 2 Measurements of cardiac function in WT and *Anxa1*^{-/-} mice: (a) EF, (b) FS and (c) FAC at week 13, and (d) intra-ventricular septum diameter (IVSd). (e–g) Densitometric analysis of bands is expressed as relative to sham absorbance of (e) phosphorylated p38 (pThr¹⁸⁰/Tyr¹⁸²) corrected to total p38 and normalised using the WT + vehicle band, (f) phosphorylated JNK (pThr¹⁸³/Tyr¹⁸⁵) corrected to total JNK and normalised using the WT + vehicle band, and (g) phosphorylated ERK1/2 (p-Thr²⁰²/-Tyr²⁰⁴) corrected to total ERK1/2 and normalised using the WT +

vehicle band. Experimental groups: WT + vehicle (100 μ l, 0.1 mol/l citrate buffer, i.p. for 5 days), WT + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days), *Anxa1*^{-/-} + vehicle (100 μ l, 0.1 mol/l citrate buffer, i.p. for 5 days) and *Anxa1*^{-/-} + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days). Black bars, vehicle; white bars, STZ. In (g) solid bars, ERK1; hatched bars, ERK2. Data analysed by a one-way ANOVA followed by a Bonferroni post hoc test and expressed as mean \pm SEM. $n = 6–8$ per group. * $p < 0.05$

demonstrated a significant increase in intra-ventricular septum thickness, suggesting the presence of severe concentric hypertrophy (Fig. 2d and ESM Fig. 3a–d).

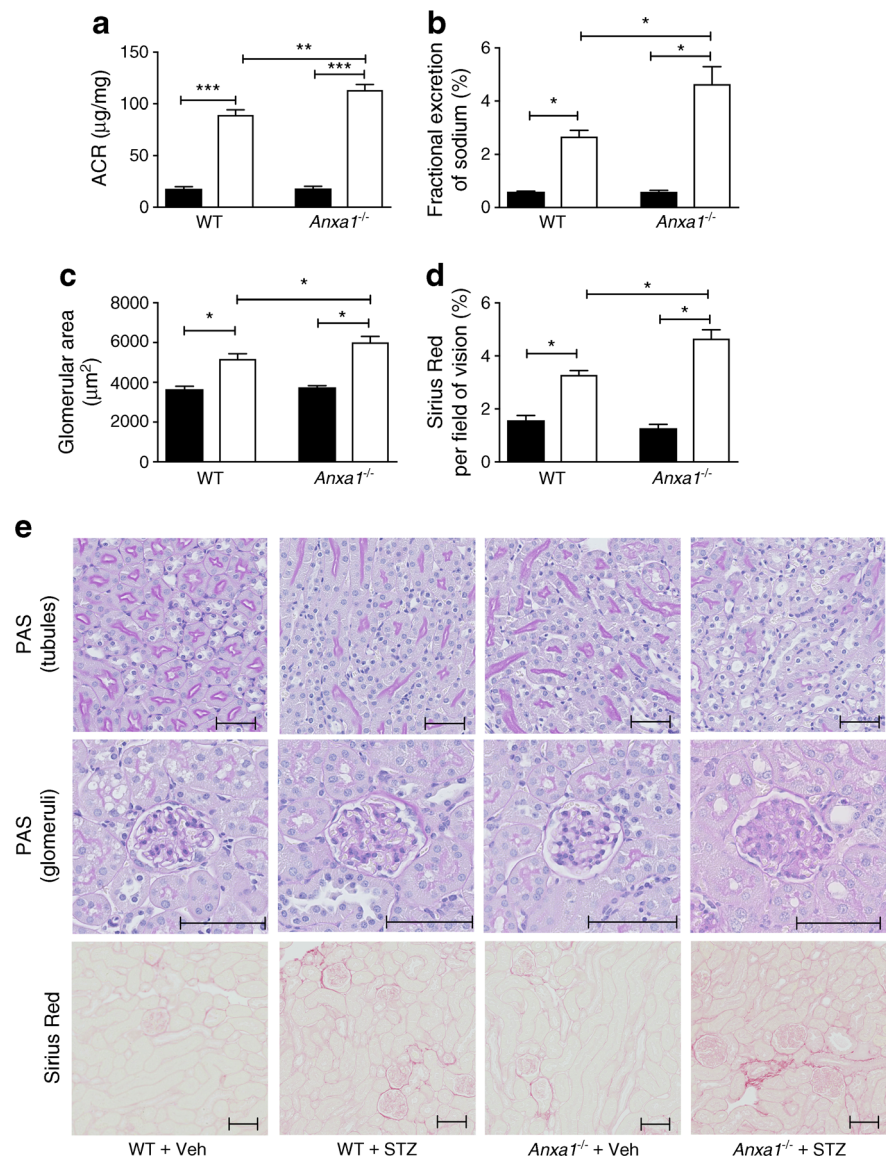
Western blot analysis of tissue from the hearts of mice demonstrated that, compared with non-diabetic WT mice, diabetic WT mice demonstrated a significant increase in the degree of phosphorylation of Thr¹⁸⁰/Tyr¹⁸² on p38, Thr¹⁸³/Tyr¹⁸⁵ on JNK and Thr²⁰²/Tyr²⁰⁴ on ERK1/2 (Fig. 2e–g). Interestingly, compared with non-diabetic WT mice, non-diabetic *Anxa1*^{-/-} mice demonstrated significantly more phosphorylation of Thr¹⁸⁰/Tyr¹⁸² on p38, Thr¹⁸³/Tyr¹⁸⁵ on JNK and Thr²⁰²/Tyr²⁰⁴ on ERK1/2, suggesting activation at basal state, while diabetic *Anxa1*^{-/-} mice demonstrated a further increase in the degree of phosphorylation of Thr¹⁸⁰/Tyr¹⁸² on p38, Thr¹⁸³/Tyr¹⁸⁵ on JNK and Thr²⁰²/Tyr²⁰⁴ on ERK1/2 (Fig. 2e–g).

Diabetic *Anxa1*^{-/-} mice have more severe renal dysfunction as a result of STZ-induced type 1 diabetes To investigate the role of endogenous ANXA1 on renal dysfunction associated with STZ-induced diabetes, renal function was assessed using urinary variables. When compared with non-diabetic WT mice, diabetic WT mice demonstrated a

significant increase in urinary albumin-to-creatinine ratio (ACR) (Fig. 3a) and fractional excretion of sodium (Fig. 3b), indicating the presence of proteinuria and tubular dysfunction, which was further exacerbated in diabetic *Anxa1*^{-/-} mice (Fig. 3a, b).

Histological analysis of renal tissue from non-diabetic WT mice and *Anxa1*^{-/-} mice demonstrated no morphological alterations, including a well-preserved brush border in the S1–S2 segment of the proximal convoluted tubules (PCT) and normal glomerular structures at basal state (Fig. 3e). However, kidneys from diabetic WT mice demonstrated PCT dilation, a marked increase in the degree of vascular degeneration and a loss of brush borders in the S1–S2 segment of the PCT, demonstrating morphological features consistent with renal dysfunction, specifically tubular dysfunction (Fig. 3e). Kidneys from diabetic WT mice also exhibited an increase in glomerular size (Fig. 3c, e), suggesting glomerular hypertrophy consistent with observed renal dysfunction and proteinuria. All histological markers were further exacerbated in the kidneys from diabetic *Anxa1*^{-/-} mice (Fig. 3e), specifically the observed loss of brush border in the S1–S2 segment of the PCT. Diabetic WT mice also exhibited significant increase in Sirius Red

Fig. 3 Measurements of renal function in WT and *Anxa1*^{-/-} mice: (a) urine ACR, (b) fractional excretion of sodium, (c) glomerular area and (d) quantification of Sirius Red staining. (e) Representative images of periodic acid–Schiff's (PAS) staining of tubules and glomeruli, and Sirius Red staining. Experimental groups: WT + vehicle (Veh; 100 μ l, 0.1 mol/l citrate buffer, i.p. for 5 days); WT + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days); *Anxa1*^{-/-} + vehicle (100 μ l, 0.1 mol/l citrate buffer, i.p. for 5 days) and *Anxa1*^{-/-} + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days). Black bars, vehicle; white bars, STZ. Scale bars, 100 μ m. Data analysis was performed by a one-way ANOVA followed by a Bonferroni post hoc test and expressed as mean \pm SEM. $n = 6$ –8 per group. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$



staining for collagen I and III in the interstitial spaces (Fig. 3d, e), indicating the development of renal fibrosis, while kidneys from diabetic *Anxa1*^{-/-} mice had significantly more Sirius Red staining specifically in the interstitial spaces and around the vasculature (Fig. 3d, e).

Western blot analysis of the tissue from the kidneys of diabetic WT mice demonstrated a significant increase in the degree of phosphorylation of Thr¹⁸⁰/Tyr¹⁸² on p38, Thr¹⁸³/Tyr¹⁸⁵ on JNK and Thr²⁰²/Tyr²⁰⁴ on ERK1/2 (Fig. 4). Interestingly, compared with non-diabetic WT mice, non-diabetic *Anxa1*^{-/-} mice demonstrated significantly more phosphorylation of Thr¹⁸⁰/Tyr¹⁸² on p38 and Thr¹⁸³/Tyr¹⁸⁵ on JNK at basal state (Fig. 4a, b), while diabetic *Anxa1*^{-/-} mice demonstrated a further increase in the degree of phosphorylation of

Thr¹⁸⁰/Tyr¹⁸² on p38, Thr¹⁸³/Tyr¹⁸⁵ on JNK and Thr²⁰²/Tyr²⁰⁴ on ERK1/2 (Fig. 4).

Prophylactic daily treatment with hrANXA1 protects against cardiac and renal dysfunction caused by STZ-induced model of type 1 diabetes

When compared with untreated diabetic mice, diabetic mice treated with daily hrANXA1 from weeks 1–13 or during days 1–5 exhibited no change in serum insulin level, non-fasted blood glucose or OGTT (Table 1), suggesting treatment with hrANXA1 did not alter the underlying diabetic phenotype. When left ventricular function was assessed using echocardiography, diabetic mice had reduced EF, FS and FAC compared with non-diabetic mice (Fig. 5a–c). Treatment with hrANXA1 from weeks 1–13 significantly attenuated the decreases in EF, FS

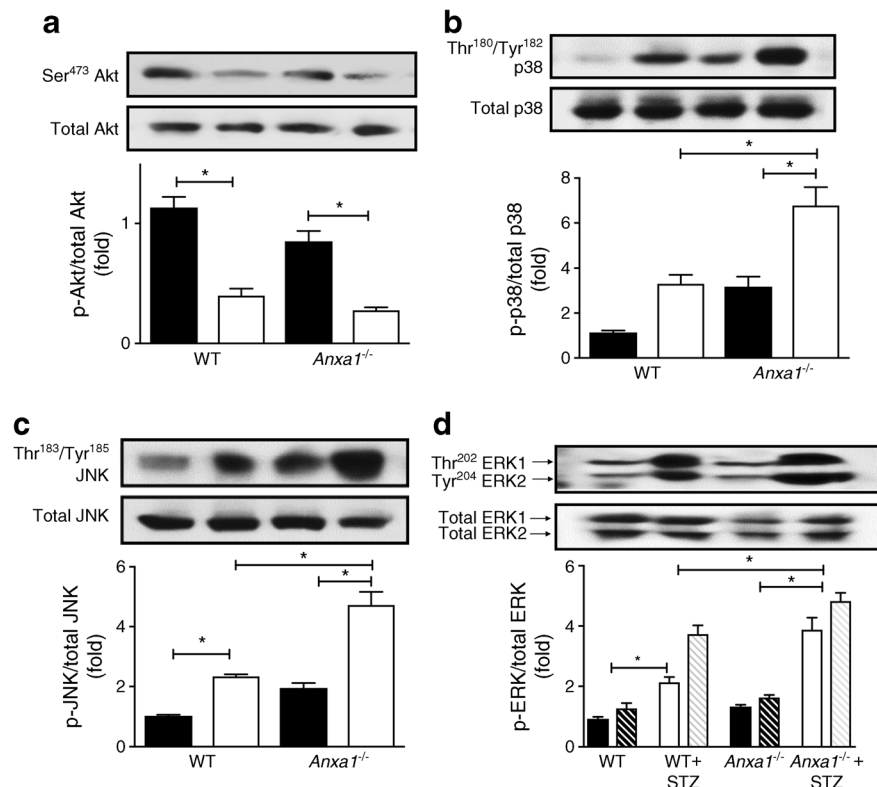


Fig. 4 Signalling in the kidney was assessed 13 weeks after STZ induction of type 1 diabetes mellitus. Densitometric analysis of bands is expressed relative to sham absorbance of (a) phosphorylated Akt (pSer⁴⁷³) corrected to total Akt and normalised using the WT + vehicle band; (b) phosphorylated p38 (pThr¹⁸⁰/Tyr¹⁸²) corrected to total p38 and normalised using the WT + vehicle band; (c) phosphorylated JNK (pThr¹⁸³/Tyr¹⁸⁵) corrected to total JNK and normalised using the WT + vehicle band; and (d) phosphorylated ERK1/2 (pThr²⁰²/Tyr²⁰⁴) corrected to total ERK1/2 and normalised using the WT + vehicle band.

Experimental groups: WT + vehicle (100 μ l, 0.1 mol/l citrate buffer, i.p. for 5 days); WT + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days); *Anxa1*^{-/-} + vehicle (100 μ l, 0.1 mol/l citrate buffer, i.p. for 5 days) and *Anxa1*^{-/-} + STZ (45 mg/kg, 0.1 mol/l citrate buffer, i.p. for 5 days). Representative images from one of three repeated experiments are shown. Black bars, vehicle; white bars, STZ. In (d): solid bars, ERK1; hatched bars, ERK2. Data analysed by a one-way ANOVA followed by a Bonferroni post hoc test and expressed as mean \pm SEM. $n = 6$ –8 per group. * $p < 0.05$

and FAC (Fig. 5a–c) suggesting that daily treatment with hrANXA1 (from weeks 1–13) protects against the development of cardiac dysfunction.

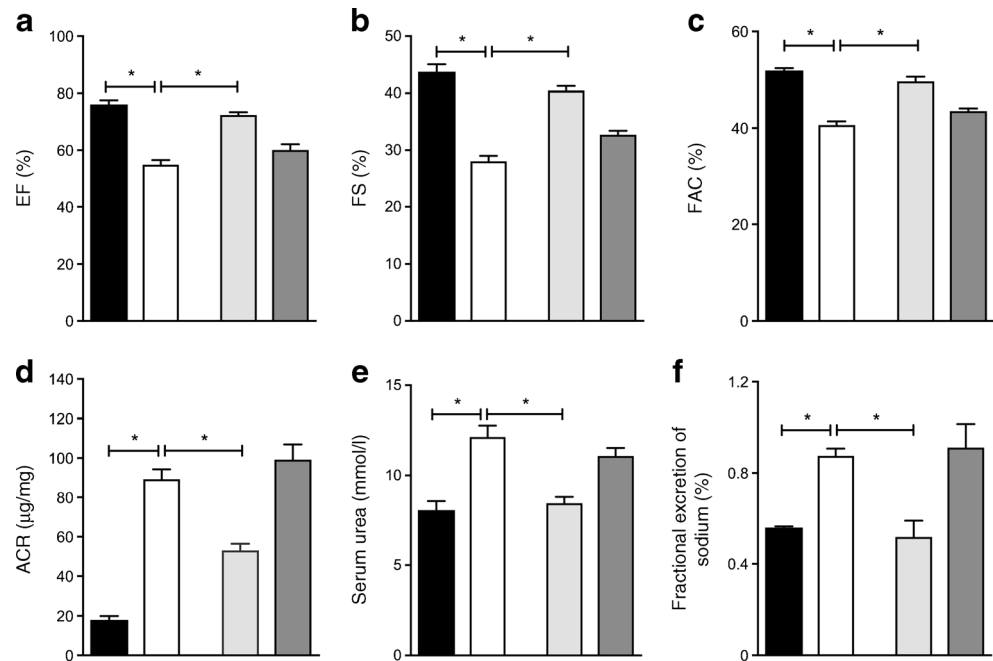
Similarly, when renal function was assessed, diabetic mice demonstrated significantly elevated ACR, serum urea and fractional excretion of sodium, while treatment with hrANXA1 from weeks 1–13 significantly attenuated these increases (Fig. 5d–f). These findings suggest that hrANXA1 protects against the development of renal dysfunction caused by STZ-induced diabetes. Treatment with hrANXA1 on days 1–5 had no effect on EF, FS, FAC, ACR, serum urea or fractional excretion of sodium (Fig. 5a–f).

Therapeutic treatment (weeks 8–13) with hrANXA1 halts the progression of renal and cardiac dysfunction caused by STZ-induced type 1 diabetes When compared with diabetic mice, diabetic mice given therapeutic treatment of hrANXA1 (weeks 8–13) exhibited no difference in insulin

levels, non-fasted blood glucose and OGTT impairment (Table 1). When left ventricular function was assessed using echocardiography, diabetic mice demonstrated a significant reduction in EF, FS and FAC (Fig. 6a–c) from week 7 to week 13. Interestingly, mice given therapeutic treatment with hrANXA1 (weeks 8–13) demonstrated no decline in EF, FS and FAC (Fig. 6a–c) from week 7 to week 13, suggesting that late treatment with hrANXA1 can halt the progression of cardiac dysfunction.

Similarly, renal function was assessed at weeks 7 and 13, diabetic mice demonstrated a significant increase in ACR, serum urea and fractional excretion of sodium (Fig. 6d–f) from week 7 to week 13. Interestingly, mice given therapeutic treatment with hrANXA1 (weeks 8–13) demonstrated no significant increase in serum urea and fractional excretion of sodium (Fig. 6e, f), suggesting that late treatment with hrANXA1 may reduce progression of tubular dysfunction associated with STZ-induced diabetes. However, ACR did increase but not to the same degree as

Fig. 5 Measurement of cardiac and renal function after prophylactic administration of hrANXA1 (weeks 1–13): **(a)** EF, **(b)** FS **(c)** FAC, **(d)** urine ACR, **(e)** serum urea and **(f)** fractional excretion of sodium. Experimental groups: sham (no STZ; black bars); STZ + vehicle (white bars); STZ + hrANXA1 weeks 1–13 (1 µg hrANXA1, i.p. daily weeks 1–13; light grey bars); STZ + hrANXA1 days 1–5 (1 µg hrANXA1, i.p. for 5 days; dark grey bars). Data analysed by a one-way ANOVA followed by a Bonferroni post hoc test and expressed as mean ± SEM. $n = 6–8$ per group. * $p < 0.05$



in mice treated with vehicle (Fig. 6d), suggesting a small but significant reduction in proteinuria.

Treatment with hrANXA1 restores normal signalling events in the heart and kidney after STZ-induced type 1 diabetes Diabetic mice exhibited a significant increase in the degree of phosphorylation of Thr¹⁸⁰/Tyr¹⁸² on p38, Thr¹⁸³/Tyr¹⁸⁵ on JNK and Thr²⁰²/Tyr²⁰⁴ on ERK1/2 in both the heart and kidney (Fig. 7) compared with WT mice. Moreover, treatment with hrANXA1 from weeks 1–13 attenuated the increase in phosphorylation of Thr¹⁸⁰/Tyr¹⁸² on p38, Thr¹⁸³/Tyr¹⁸⁵ on JNK and Thr²⁰²/Tyr²⁰⁴ on ERK1/2 in both the heart and kidney (Fig. 7). Similarly, therapeutic treatment with hrANXA1 (weeks 8–13) attenuated the increase in phosphorylation of Thr¹⁸³/Tyr¹⁸⁵ on JNK and Thr²⁰²/Tyr²⁰⁴ on ERK1/2 in both the heart and kidney (Fig. 7d, f), and Thr^{180/182} on p38 in the heart (Fig. 7a).

Diabetic mice exhibited significantly less phosphorylation of Ser⁴⁷³ on Akt in the heart and kidney (Fig. 7g, h) compared with non-diabetic mice. Such data suggest that Akt signalling is blunted and could be restored when mice were treated with hrANXA1 from weeks 1–13 in both the heart and kidney, while therapeutic treatment with hrANXA1 (weeks 8–13) also restored the phosphorylation of Ser⁴⁷³ of Akt in the heart but not the kidney.

Discussion

ANXA1 levels are elevated in individuals with type 1 diabetes. The main conceptually novel findings of this study are: (1) *Anxa1*^{-/-} mice challenged with STZ developed a more severe

diabetic phenotype and more severe systolic cardiac and renal dysfunction compared with diabetic WT mice; (2) prophylactic treatment of diabetic mice with hrANXA1 did not prevent the development of a diabetic phenotype but attenuated the development of both cardiac and renal dysfunction; and (3) therapeutic administration of hrANXA1 (after both cardiac and renal dysfunction had developed) halted the progression of both cardiac and renal dysfunction seen in diabetic WT mice. Thus, endogenous ANXA1 prevents the development of end-organ injury in a murine model of type 1 diabetes and therapeutic hrANXA1 prevents (prophylactic administration) or halts (late therapeutic administration) the progression of systolic cardiac dysfunction and proteinuria caused by diabetes in these animals without altering the underlying diabetic phenotype.

Type 1 diabetes is characterised by elevated blood glucose levels, which drives low-grade chronic inflammation and thus contribute to tissue/organ damage. Healthy donors have low levels of ANXA1 in plasma [26]. Here we report that ANXA1 is elevated in individuals with type 1 diabetes with and without nephropathy (Fig. 1a). Additionally, we show that diabetic individuals have elevated systemic inflammation levels, which are further elevated by nephropathy. Elevated plasma CRP is strongly associated with adverse outcomes in myocardial infarction, stroke and coronary heart disease, which are common causes of death in people with type 1 diabetes. We hypothesise that the elevation in circulating ANXA1 is a compensatory mechanism to protect tissues from the deleterious effects of hyperglycaemia, independent of the presence of diabetic nephropathy and not as a consequence of a rise in systemic inflammation (ESM Fig. 1b). ANXA1 is found in many tissues, including the heart and kidney, but is also highly

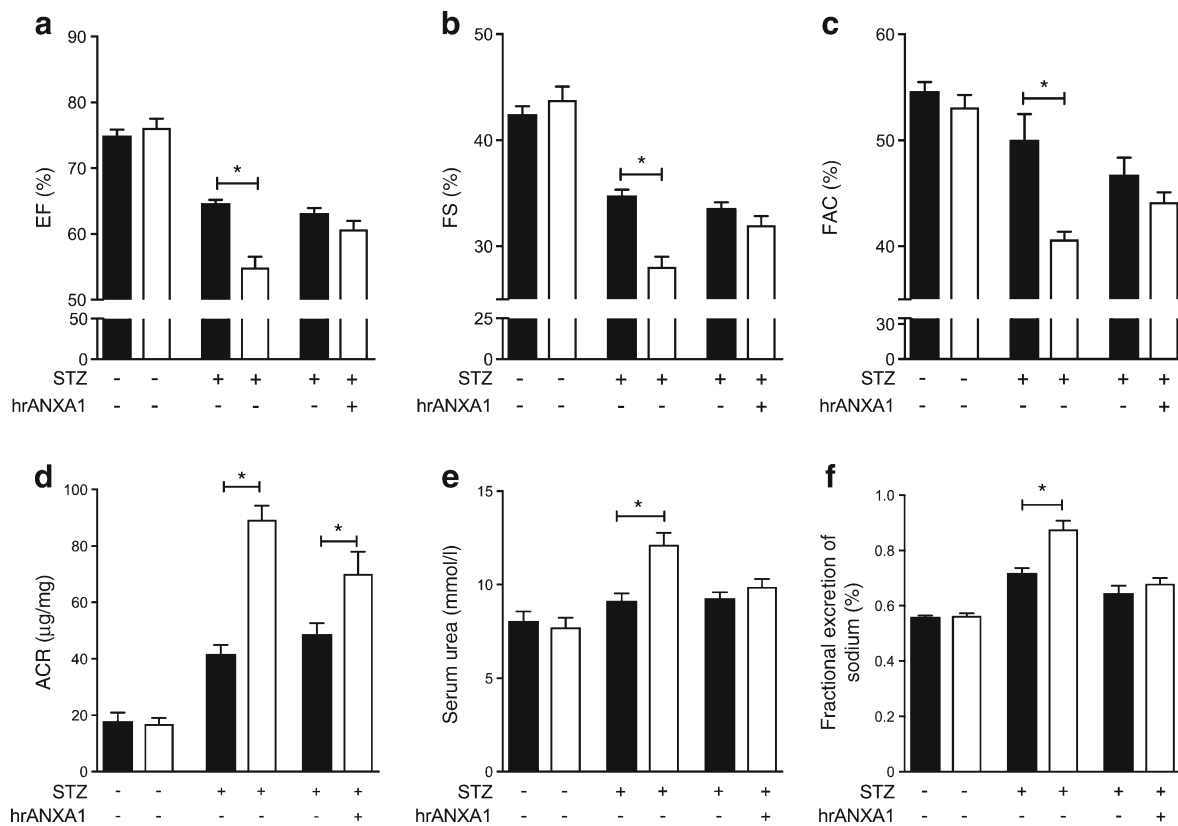


Fig. 6 Measurement of cardiac and renal function after therapeutic administration of hrANXA1 (weeks 8–13). Measurements were taken before treatment (at week 7) and after treatment (at week 13): (a) EF, (b) FS and (c) FAC, and (d) urine ACR, (e) serum urea and (f) fractional excretion of sodium. Experimental groups: sham (no STZ); STZ + vehicle;

STZ + hrANXA1 weeks 8–13 (1 µg hrANXA1, i.p. daily weeks 1–13). Black bars, 7 weeks; white bars, 13 weeks. Data analysed by a one-way ANOVA followed by a Bonferroni post hoc test and expressed as mean ± SEM. $n = 6–8$ per group. * $p < 0.05$

expressed in macrophages and other immune cells [26]. Here we report that ANXA1 levels were lower in both the heart and kidney, suggesting that hyperglycaemia causes ANXA1 to be released from tissue stores. ANXA1 secretion is needed so it can signal to the FRP2 in both an autocrine and paracrine manner to activate tissue/organ protective pathways [12, 27].

We therefore wanted to understand the role of endogenous ANXA1 in the development of type 1 diabetes and in tissue/organ protection in the mouse. Mice challenged with STZ developed a diabetic phenotype with elevated non-fasted blood glucose levels and impairment in OGTT secondary to a very large (>75%) reduction in serum insulin levels. In individuals with type 1 diabetes, beta cell mass is irreversibly reduced by 70–80% at the time of diagnosis [28]; similar loss of beta cells is recorded in mice administered STZ [29]. We report here that the diabetic phenotype (OGTT) caused by STZ is more severe in diabetic *Anxa1*^{-/-} mice, although the serum insulin levels are reduced to a similar degree (Table 1). This finding suggests that endogenous ANXA1 limits the development of hyperglycaemia in an insulin-independent manner.

Even individuals who undergo rigorous insulin management develop microvascular complications over time [30]. Here we report that diabetic *Anxa1*^{-/-} mice have more severe

cardiac and renal dysfunction compared with diabetic WT mice, suggesting that endogenous ANXA1 limits the development of end-organ injury/dysfunction in mice with diabetes (Figs 2, 3). As hypertrophy is an important contributor in diabetes-associated cardiac and renal dysfunction we evaluated both intra-ventricular septum diameter [31] and glomerular size; and report that both are significantly increased in diabetic mice (Figs 2, 3). Notably, both glomerular hypertrophy and interstitial fibrosis were further significantly augmented in diabetic *Anxa1*^{-/-} mice when compared with diabetic WT mice. Cardiac hypertrophy is a common response to external stressors, including hyperglycaemia and oxidative stress [32]; this compensatory process evolves into a decompensated state with profound changes in contractile dysfunction and extracellular remodelling [33]. Similarly, renal hypertrophy is also a compensatory mechanism [34]; in the case of type 1 diabetes, excessive renal hyperfiltration due to activation of the renin–angiotensin pathways [35] puts stress on glomeruli and proximal tubules [35], manifesting in functional decline.

Having found that endogenous ANXA1 limits the development of microvascular complications associated with diabetes, we wanted to investigate whether pharmacological intervention with hrANXA1 can attenuate the development of diabetic

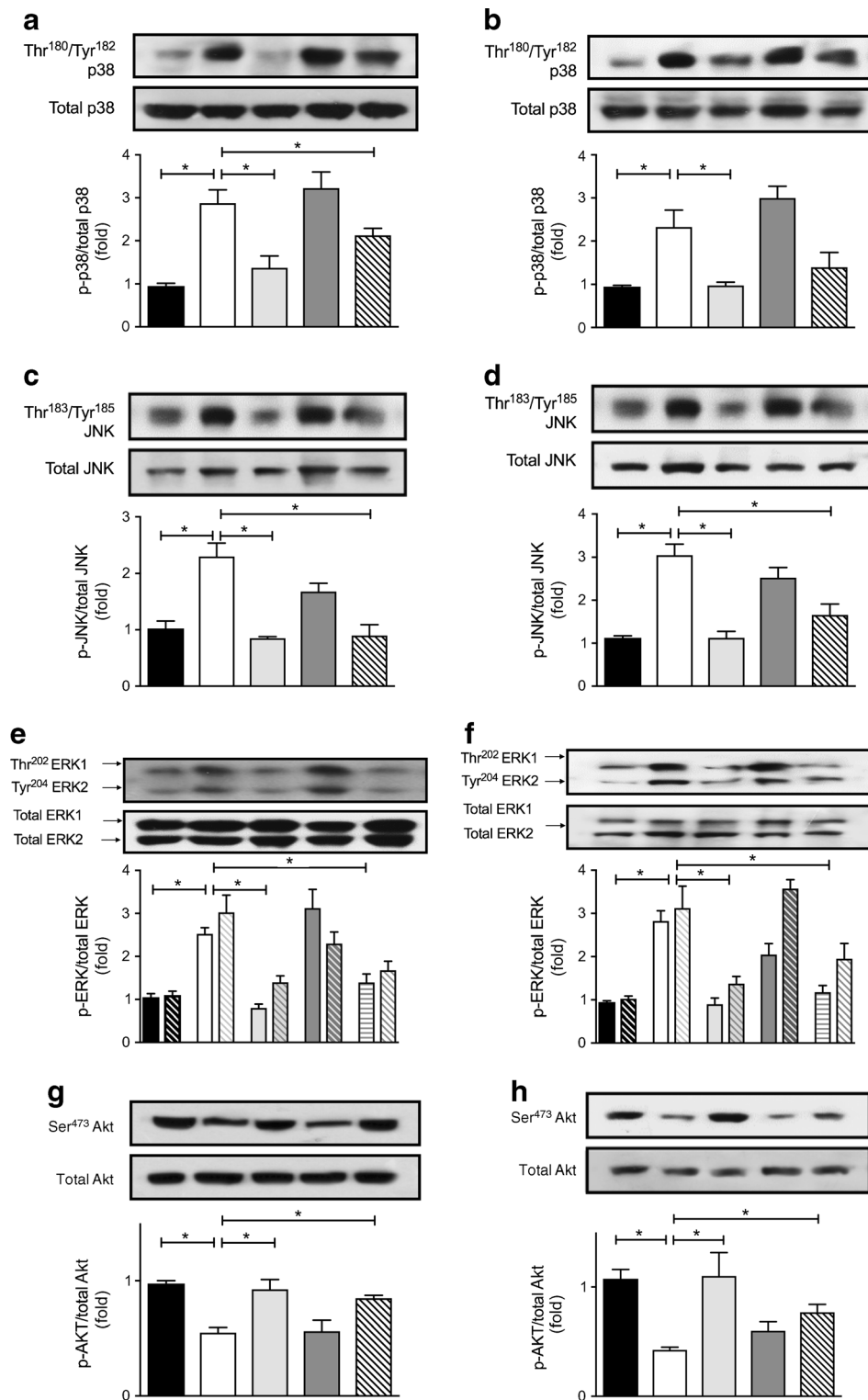


Fig. 7 Signalling in the heart (**a, c, e, g**) and kidney (**b, d, f, h**) was assessed 13 weeks after STZ induction of type 1 diabetes mellitus. Densitometric analysis of bands is expressed as relative to sham absorbance of (**a, b**) p-p38 (p-Thr¹⁸⁰/Tyr¹⁸²) corrected to total p38 and normalised using the WT + vehicle band; (**c, d**) p-JNK (p-Thr¹⁸³/Tyr¹⁸⁵) corrected to total JNK and normalised using the sham band; (**e, f**) p-ERK1/2 (p-Thr²⁰²/Tyr²⁰⁴) corrected to total ERK1/2 and normalised using the sham band; and (**g, h**) p-Akt (p-Ser⁴⁷³) corrected to total Akt and normalised using sham band. Experimental groups: sham (no STZ; black bars); STZ +

vehicle (white bars); STZ + hrANXA1 weeks 1–13 (1 μ g hrANXA1, i.p. daily weeks 1–13; light grey bars); STZ + hrANXA1 days 1–5 (1 μ g hrANXA1, i.p. for 5 days; dark grey bars) and STZ + hrANXA1 weeks 8–13 (1 μ g hrANXA1, i.p. weeks 8–13, grey hatched bars). In (**e, f**): solid bars, ERK1; hatched bars, ERK2; for the STZ + hrANXA1 weeks 8–13 condition, ERK1, horizontal hatching, ERK2, diagonal hatching. Representative images from one of three repeated experiments are shown. Data analysed by a one-way ANOVA followed by a Bonferroni post hoc test and expressed as mean \pm SEM. $n = 6–8$ per group. $*p < 0.05$

cardiomyopathy and nephropathy. Previously, both full-length ANXA1 and the Ac2-26 peptide (the N-terminal functional fragment of ANXA1) have been used in vivo and both elicit biological function [17–19]). In this study, we chose to use full-length hrANXA1, as the dose of full-length ANXA1 needed to induce biological function is up to 20 times less than that of the Ac2-26 peptide [36] and 14 times less than that needed to induce changes in gene expression in terms of molarity [37].

Treatment of mice challenged with STZ with hrANXA1 (weeks 1–13) did not alter the diabetic phenotype (reduced insulin levels, elevated blood glucose and impaired OGTT), but attenuated the cardiac dysfunction and the proteinuria caused by diabetes, suggesting that hrANXA1 reduces the cardiac and renal injury caused by hyperglycaemia and excessive oxidative stress (organ protection rather than reduction of diabetes). Most notably, we also report that a late therapeutic intervention (weeks 8–13), when a diabetic phenotype and a moderate degree of cardiac and renal dysfunction had already occurred, halted the further decline in both cardiac and renal function seen in diabetic WT mice. It should be noted that administration of ANXA1 during the administration of STZ (days 1–5) was also not sufficient to reduce the diabetic phenotype or give long-term protection to organs.

What are the mechanisms by which ANXA1 elicits protection against cardiac and renal dysfunction associated with diabetes? We show here for the first time that the development of type 1 diabetes (caused by STZ) in mice is associated with (1) a reduction in endogenous ANXA1 levels in both the heart and the kidney (increased secretion) and (2) a decline in cardiac and renal dysfunction. Thus, we speculated that endogenous ANXA1 protects both the heart and the kidney (and hence reduces organ injury/dysfunction) by acting on pro-survival and anti-inflammatory pathways.

Hyperglycaemia leads to activation (phosphorylation) of mitogen-activated protein kinases (MAPKs) p38, JNK and ERK1/2, hypertrophy and fibrosis in the heart [32–38] and kidney [39, 40]. While little evidence is available to suggest strong tissue specific activation of proinflammatory pathways in STZ-induced diabetes, pharmacological inhibition or genetic deletion of any of these three MAPKs reduces microvascular complications (diabetic nephropathy, cardiomyopathy and retinopathy) caused by type 1 diabetes in rodents [41, 42]. Indeed we found no activation of NF- κ B or the inflammasome in our model of STZ-induced diabetes (ESM Fig. 4). However, we observed a significant increase in activated (phosphorylated) p38, JNK and ERK1/2 in diabetic WT mice. Interestingly, *Anxa1*^{-/-} mice, even in the absence of diabetes (no STZ challenge), had constitutive activation (phosphorylation) of p38, JNK and ERK1/2 in the heart and kidney. The degree of activation of p38, JNK and ERK1/2 was further exacerbated when *Anxa1*^{-/-} mice were challenged with STZ. As diabetic *Anxa1*^{-/-} mice also had excessive renal hypertrophy and fibrosis, we speculate that the excessive activation of these

known proinflammatory and profibrotic signalling pathways are key drivers of the excessive pathology seen in *Anxa1*^{-/-} mice. This hypothesis is supported by the following two findings: (1) treatment of diabetic WT mice with hrANXA1 attenuated the activation of p38, JNK and ERK1/2 and the cardiac and renal dysfunction caused by diabetes; and (2) even when hrANXA1 was given therapeutically (weeks 8–13) this resulted in attenuation of the activation of p38, JNK and ERK1/2 as well as the organ dysfunction caused by diabetes.

In addition, we also investigated the effect of diabetes with or without hrANXA1 treatment on the degree of activation of Akt survival pathways, which is in part regulated by IRS-1 [43]. Diabetic mice demonstrated a significant decrease in the phosphorylation of Ser⁴⁷³ on Akt (indicating a reduction in activity of the kinase) in the heart and kidney. One effect of this inhibition is that organs are less resistant to stressor stimuli and subsequent organ injury. In contrast, treatment with hrANXA1 attenuated the decline in Akt activation caused by diabetes. Akt is a member of the phosphoinositide-3 kinase (PI3K) signal transduction pathway. Insulin signalling through IRS-1 regulates PI3K activity and PI3K can activate Akt (phosphorylation on Ser⁴⁷³). Activated Akt controls inflammatory and pro-survival responses [44]. Most notably, activation of the Akt survival pathway reduces organ injury in many conditions associated with inflammation including sepsis-induced organ dysfunction [20, 45], haemorrhagic shock-induced organ dysfunction [25, 46], myocardial infarction [47] and diabetes [48]. Specifically, in cardiac and renal ischaemia/reperfusion injury treatment with the Ac2-16 peptide tissue necrosis was reduced by activation of Akt [49, 50].

In conclusion, we report for the first time that ANXA1 levels are elevated in the plasma of individuals with type 1 diabetes. We have also clearly demonstrated that endogenous ANXA1 plays a key role in protecting the heart and kidney from functional decline in an animal model of type 1 diabetes. Specifically, we have shown that key mediators of the MAPK pathway (p38, JNK and ERK1/2) are constitutively activated in *Anxa1*^{-/-} mice. Administration of hrANXA1 attenuated both cardiac and renal dysfunction caused by STZ induction of diabetes. While late treatment can halt both cardiac and renal dysfunction. We propose that attenuation of MAPK pathway signalling and restoration/activation of Akt survival pathways mediates these effects. Thus, we propose that treatment with hrANXA1 may represent a novel new intervention of microvascular complications caused by type 1 diabetes.

Data availability All data generated or analysed during this study are included in this published article (and its [supplementary information file](#)).

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Duality of interest No conflict of interest declared.

Contribution statement All authors made substantial contributions to conception and design, acquisition of data and interpretation of data; GP, LG, MC, CT and ES drafted the manuscript and provided important intellectual content; all authors reviewed and approved the manuscript. GP, CT and ES are the guarantors of this work.

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