Protection by vitamin D against high-glucose-induced damage in retinal pigment epithelial cells

Tohari, Ali Mohammad; Almarhoun, Mohammad; Alhasani, Reem Hasaballah; Biswas, Lincoln; Zhou, Xinzhì; Reilly, James; Zeng, Zhihong; Shu, Xinhua

Published in:
Experimental Cell Research

DOI:
[10.1016/j.yexcr.2020.112023](https://doi.org/10.1016/j.yexcr.2020.112023)

Publication date:
2020

Document Version
Author accepted manuscript

[Link to publication in ResearchOnline](#)

Citation for published version (Harvard):

Tohari, AM, Almarhoun, M, Alhasani, RH, Biswas, L, Zhou, X, Reilly, J, Zeng, Z & Shu, X 2020, 'Protection by vitamin D against high-glucose-induced damage in retinal pigment epithelial cells', *Experimental Cell Research*, vol. 392, no. 1, 112023. <https://doi.org/10.1016/j.yexcr.2020.112023>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please view our takedown policy at <https://edshare.gcu.ac.uk/id/eprint/5179> for details of how to contact us.

Protection by vitamin D against high-glucose-induced damage in retinal pigment epithelial cells

Ali Mohammad Tohari^{1, 2}, Mohammad Almarhoun², Reem Hasaballah Alhasani^{2,5}, Lincoln Biswas²,
Xinzhi Zhou², James Reilly², Zhihong Zeng^{3,*} and Xinhua Shu^{2,4*}

¹Department of Clinical Biochemistry, King Fahad Hospital, Jazan, PO Box 204, 91991, Saudi
Arabia

²Department of Biological and Biomedical Sciences, Glasgow Caledonian University, Glasgow G4
0BA, United Kingdom

³College of Biological and Environmental Engineering, Changsha University, Changsha, Hunan
410022, P. R. China

⁴Department of Vision Science, Glasgow Caledonian University, Glasgow G4 0BA, United Kingdom

⁵Department of Biology, Faculty of Applied Science, Umm Al-Qura University, Makkah, Saudi
Arabia

* Corresponding authors: z20181201@ccsu.edu.cn; Xinhua.Shu@gcu.ac.uk

Abstract

Diabetic retinopathy (DR) is a diabetes-associated complication characterized by irreversible deterioration of the microvessels within the retina, leading subsequently to severe retinal damage and vision loss. Vitamin D (VITD), a steroid hormone, plays multiple physiological functions in cellular homeostasis. Deficiency of VITD has been suggested to be associated with DR. To study the potential protective function of VITD in DR, high-glucose-treated ARPE-19 cells and STZ-induced diabetic mice were used as *in vitro* and *in vivo* models. The protective effects of VITD were assessed based on the changes of expression of antioxidant enzymes and cytokines in high-glucose-treated RPE cells and in the retina and retinal pigment epithelium (RPE) of diabetic and VITD-treated diabetic mice. The present study demonstrated that exposure to a high level of glucose caused upregulation of pro-inflammatory cytokines and a decrease in anti-oxidant enzyme expression in both *in vitro* and *in vivo* models. VITD treatment increased cell viability, reduced reactive oxygen species (ROS) production and caspase-3/7 activities in high-glucose-treated RPE cells. Our data suggest that VITD can protect the retina and RPE from high-glucose-induced oxidative damage and inflammation.

Keywords diabetic retinopathy; vitamin D; oxidative stress; inflammation; protection

1. Introduction

Diabetic retinopathy (DR) is a microvascular consequence of diabetes mellitus. DR is defined as the progressive irreversible deterioration of the tiny blood vessels within the retina as a result of chronic hyperglycemia, leading to severe damage of the retinal microvasculature and associated vision problems including blindness [1]. DR can develop in both type 1 and type 2 diabetes mellitus. The incidence of DR is believed to be influenced by factors such as type and duration of diabetes, age, ethnicity and genetic susceptibility. DR can occur after the onset of diabetes and the development of DR is strongly associated with the duration and the management of diabetes. Pooled epidemiologic studies have explored the global incidence of DR and have concluded that there has been a significant increase of DR among type 1 and type 2 diabetes patients worldwide, estimated to range from 8% at 3 years to 100% at 15-20 years after diabetes onset [2,3].

Glucose is the main source of energy at the cellular level. Insulin is the principal regulator of glucose metabolism. Insulin deficiency or resistance can cause the significant disturbance in glucose metabolism that is the main characteristic of diabetes. Prolonged high plasma glucose concentration can cause severe diabetic complications, including DR. Although DR is recognized as a multifactorial disease, impairment of glucose metabolism is its primary cause. Previous studies have investigated molecular mechanisms of DR caused by hyperglycemia [1,4,5]. The retina has a high metabolic activity and oxygen consumption. Thus, chronic hyperglycemia and insulin deficit or resistance can alter glucose metabolism from normal glycolysis to other metabolic pathways and can produce reactive biochemical molecules that are capable of inducing irreversible damage in the retina. Several studies have shown that diabetes can trigger DR by increasing the production of free radicals from diverted glucose metabolism pathways including the polyol pathway, nonenzymatic glycosylation, hexosamine pathway, activation of PKC and poly (ADP-ribose) polymerase pathways [1,4,5]. A number of antioxidants have demonstrated protective effects in DR animal models, offering therapeutic potential for DR patients [6,7].

It is well established that inflammation contributes to DR development and progression [7-12]. Recent computational analyses of microarray datasets have demonstrated that the

pathogenesis of DR is linked to inflammation and fibrosis [8]. Increased production of proinflammatory cytokines, such as IL-1, TNF- α and VEGF, have been reported in the vitreous of DR patients and in the retinas of DR animal models [7,9]. High-glucose-induced upregulation of proinflammatory cytokines can cause breakdown of the blood-retinal barrier (BRB), cell death and angiogenesis [7,10]. VEGF-A is the major angiogenic factor and contributes to the pathogenesis of diabetic macular edema [7]. VEGF-A production induced by high glucose is mediated by a variety of signalling pathways, such as PKC, ERK and HIF pathways (6,7,11). Recently Platania et al. demonstrated that miRNAs also mediate VEGF expression [12]. Currently anti-VEGF strategy is effective in treating diabetic macular edema. However, other therapeutic strategies are urgently needed for preventing and/or slowing the progression of DR [7].

Vitamin D (VITD), a secosteroid hormone, is found in many types of food and is also endogenously produced in humans. VITD is found in two forms in biological systems: the inactive form 25(OH)2D3 and the active form 1,25(OH)2D3. The active form of VITD is the principal regulator of calcium and phosphate ions; however, it is also involved in regulating gene expression in targeted cells and organs via genomic and non-genomic mechanisms [13]. VITD deficiency has been associated with ageing and with a range of diseases [14]. VITD deficiency is also linked with higher risk of retinopathy in type1 and 2 diabetic patients [15-17]. Lower serum VITD concentration is associated with increased severity of retinopathy in patients with proliferative DR [18,19]. Previous studies also reported that polymorphisms (*Apal*, *BsmI*, *FokI* and *Taq I*) in the vitamin D receptor (VDR) gene are associated with increased risk of retinopathy in diabetic patients [20-22]. However, the mechanisms of VITD involvement in DR are not fully understood.

In the present study we have examined the protective role of VITD against oxidative stress and inflammation in retinal pigment epithelial (RPE) cells under high glucose condition. We found that VITD increased antioxidant capacity and inhibited inflammation *in vitro* and *in vivo*.

2. Materials and methods

2.1. Cell viability

ARPE-19 cells were cultured till confluence in a T-25 cm² flask containing 5 ml DMEM/F12 medium (Cat. BE12-719F, Lonza). The cells were detached using 0.5% trypsin-EDTA and seeded in 96-well plates at a density of 50,000 cells/well in DMEM containing normal glucose (5 mM and 0.1% ethanol) or high glucose (25 mM and 0.1% ethanol). Cells were treated with or without VITD (50 nM) for 6 hours or 24 hours. VITD (Cat. D9257, Sigma, UK) was dissolved in ethanol and a dose of 50 nM VITD was chosen based on our previous studies [23,24]. Cell viability was measured using the MTT assay (Sigma, UK) according the manufacture's guidance.

2.2. Biochemical assays

Caspase 3/7 activity was measured with a kit (Cat. G8090) from Promega according to the manufacturer's instructions; activities of catalase (Cat. STA-341) and superoxide oxidative dismutase (SOD, Cat. STA-340) were measured using kits from Cambridge Bioscience following the manufacturer's guidance. The levels of glutathione (GSH, Cat. STA-312) and malondialdehyde (MDA, Cat. STA-330) were assessed according to our previous description [24].

2.3. Enzyme-linked immunosorbent assay (ELISA)

ELISA was performed to detect human IL-1 β (Cat. 900-TM95), IL-8 (Cat. 900-M18), IL-33 (Cat. 900-M398), TNF- α (Cat. 900-M25) and VEGF-A (Cat. 900-M10) in cultured media from ARPE-19 cells cultured 12-well plates and to detect mouse IL-33 (Cat. 14-8332-80) and VEGF-A (Cat. 900-M99) in the lysates from mouse retinas and retinal pigment epithelial cells. The ELISA kit for mouse IL-33 was purchased from eBioscience; all other ELISA kits were from PeproTech. The detection of individual cytokines was performed according to the manufacturers' guidance.

2.4. Quantification of reactive oxygen species (ROS)

ARPE-19 cells were seeded in 96-well plates (25,000 cells/well) in DMEM-F12 medium for 24 hours. Cells were then treated with high glucose (25 mM and 0.1% ethanol) or a mixture of high glucose and VITD in DMEM for 6 or 24 hours, while control cells were treated with 0.1% ethanol only in DMEM containing normal glucose (5 mM). Cells were washed with PBS and incubated with 10 μ M DCFH-DA (6-Carboxy-2',7'-Dichlorofluorescein diacetate) for one hour. ROS production was measured according to previous description [24].

2.5 Quantitative real-time polymerase chain reaction (qRT-PCR)

Total RNAs were extracted from cultured cells or mouse tissues using TRIzol™ Reagent (Thermo Fish Scientific, UK) following the manufacturer's protocol. cDNA was set up using the High-Capacity cDNA Reverse Transcription kit (Thermo Fisher Scientific, UK) according to the manufacturer's guidance. Gene expression was detected using Platinum SYBR Green reagents following the manufacturer's protocol. Primers used for qRT-PCR are listed in Table S1.

2.6. Western blotting

Control and treated cells were collected and lysed using lysis buffer (T-PER, Thermo Scientific, UK) containing proteinase inhibitor. The concentration of the extracted protein was determined using a Bradford protein assay (DCTM protein assay kit, Bio-Rad, UK) in a 96-well microtitre plate. Individual samples (50µg/each) were loaded to the pre-cast protein gel (Bio-Rad, No. 4569034, Mini PROTEAN TGX Gel) then electrophoresed for 45 minutes at 200V in the running buffer. Separated proteins in the pre-cast gel were transferred into nitrocellular membrane, following which the membrane was blocked with milk/TBST buffer containing 5% milk powder (w/v), tris-buffered saline and 0.1% Tween 20 for one hour at room temperature. The blocked membrane was incubated with anti-NRF2 (1:1000, Cat. LS-C31637, LifeSpan BioSciences, USA) or with anti-GAPDH antibody (1:1000, Cat. 60004-1-Ig, Protentech, UK) in milk/TBST buffer overnight at 4°C. The primary antibody solution was discarded and the membrane was washed three times with TBST (15 minutes each wash). The membrane was then incubated at room temperature for 1h with the secondary antibody solution (goat anti-rabbit antibody, Cat. No. 926-32211 or donkey anti-mouse antibody, Cat. No. 926-68072 (1:10000 diluted in milk/TBST solution and then washed five times (20 minutes each wash) using TBST. The membrane was subjected to a final wash with PBS for 10 minutes and scanned using the LI-COR Odyssey FC Imaging System. The signal intensity of NRF2 or GAPDH was analyzed with the Image Studio™ Lite analysis software (LI-COR Biosciences, USA).

2.7. Assessment of VITD toxicity, induction of type 1 diabetic (T1D) mouse model and vitamin D treatment

The potential toxicity of VITD was evaluated by administering three intraperitoneal (IP) injections per week of 2.5 µg/kg of VITD or equivalent volume of carrier solution to six C57BL/6 mice (three mice were treated with VITD while the other three received only carrier solution). The chosen dose of VITD was based on previous *in vivo* studies in mice [25-27]. VITD was dissolved in ethanol (10µg/ml) and diluted in corn oil for IP injection. Prior to injection, animal weight and blood glucose were recorded. All animals received twelve IP injections of either VITD or equivalent volume of corn oil (control group) over a 4-week treatment course. The toxicity of VITD was assessed on the basis of daily monitoring of each animal's survival and weight. At the end of this experiment, weight and blood glucose were recorded and all mice were sacrificed using a Schedule One method.

Type I diabetes (T1D) was induced in eighteen mice (6 weeks old) by three consecutive IP injections of Streptozotocin (STZ, 55 mg/kg, dissolved in the citrate buffer, 0.1M citric acid, pH 4.5) according to protocols described by Feilt-Leichman et al. (2005) and Talahalli et al. (2009) [28, 29]. The control group (8 mice) received IP injections of equivalent volume of the citrate buffer. Development of diabetes was defined as a random blood glucose concentration greater than 13.5 mM. The weight and blood glucose level of each animal were monitored every two weeks over a period of 8 months for all animals. The STZ-induced T1D mice were supplied with 10% sucrose (w/v, every 2-3 days) to avoid sudden hypoglycaemia.

After 8 months of T1D, eight diabetic mice were given 12 intraperitoneal injections with VITD (2.5 µg/kg) over a 4-week treatment course; eight diabetic mice received 12 intraperitoneal injections with corn oil over the same time course (control group). All mice were housed in the same conditions for another 4 weeks. The weight and blood glucose of each animal were recorded every two weeks. At the end of this experiment, weight and blood glucose were recorded. The average animal weight was 34.12 g ± 1.27, while the average blood glucose concentration was 19.30 mM ± 3.03. All mice were sacrificed by a Schedule One method. Blood and eye samples were collected

for experiments. To dissect retinas and RPE cells, individual eyes were placed in a 35 mm petri dish and merged with 1X PBS. Muscles, optic nerves and connective tissues were removed using two pairs of sharp-angled forceps. With the cornea facing upward, a small puncture was created using sharp forceps in the center of the eye. The eye was incised around the cornea, the cornea was removed and the lens was exposed. The retina was gently peeled off from the lens. Similarly, the retinal pigment epithelium (RPE) was isolated by removing any loose remnants of the iris.

All animal experiments were performed in accordance with the UK Home Office Animals (Scientific Procedures) Act 1986 (Project licence P8C815DC9).

2.8. Data analysis

Experimental data were statistically analysed by non-parametric Kruskalis-Wallis followed by Dunn's multiple comparison test using GraphPad Prism version 6 software. $p < 0.05$ was recognized as significance. Data were presented as mean $\pm$ standard deviation.

3. Results

3.1. Vitamin D increased cell viability and reduced ROS production in human RPE cells

ARPE-19 cells treated with 25 mM glucose showed a significant decrease in cell viability at both 6 and 24 hours compared to cells cultured in physiological conditions (5 mM glucose and 0.1% ethanol). VITD treatment (50 nM) significantly improved cell viability in normal glycemic conditions at 24 hours compared to untreated cells (0.1% ethanol); in cells treated with a combination of 25 mM glucose and 50 nM VITD there was a significant increase in cell viability at both 6 and 24 hours compared to cells treated with 25 mM glucose alone (Figure 1A).

High glucose has been shown to cause increased intracellular ROS production [30]. We also found a significant increase in ROS production at both 6 and 24 hours in ARPE-19 cells treated with 25 mM glucose compared to cells treated with 5 mM glucose. ROS production was significantly reduced in cells treated for both 6 and 24 hours with a combination of 25 mM glucose and 50 nM VITD compared to cells treated with 25 mM glucose alone (Figure 1B).

Increased ROS can promote apoptosis [31]. We examined Caspase 3/7 activity, an indicator of apoptosis, and found a significant increase in Caspase 3/7 activity in ARPE-19 cells treated for both 6 and 24 hours with 25 mM glucose compared to cells treated with 5 mM glucose (0.1% ethanol). Co-treatment with VITD and 25 mM glucose significantly reduced Caspase 3/7 activity compared to cells treated with 25 mM glucose alone for both 6 and 24 hours (Figure 1C).

3.2. Vitamin D enhanced expression of antioxidant genes in human RPE cells

Given that ARPE-19 cells cultured in high glucose conditions had increased ROS production, we examined the expression of antioxidant genes and found that catalase (CAT) was significantly reduced in cells treated with 25 mM glucose compared to cells treated with 5 mM glucose (0.1% ethanol) for both 6 and 24 hours; expression of CAT was significantly increased in cells treated with a combination of 25 mM glucose and VITD compared to cells treated with 25 mM glucose alone for both 6 and 24 hours (Figure 2A).

A significant reduction of SOD1 expression was observed in ARPE-19 cells treated with 25 mM glucose compared to cells treated with 5 mM glucose (0.1% ethanol); expression of SOD1 was significantly increased in cells co-treated with 25 mM glucose and VITD compared to cells treated with 25 mM glucose alone for both 6 and 24 hours (Figure 2B). Similarly, expression of SOD2 was significantly reduced in cells treated with 25 mM glucose compared to cells treated with 5 mM glucose (0.1% ethanol), while expression of SOD2 was notably increased in cells co-exposure to 25 mM glucose and VITD compared to cells treated with 25 mM glucose alone for both 6 and 24 hours (Figure 2C).

GPX1 expression in ARPE-19 cells was not significantly changed following treatment for 6 or 24 hours with 5 mM glucose (0.1% ethanol), 25 mM glucose or a combination of 25 mM glucose and VITD (Figure 2D). Expression of GPX2 was significantly reduced in cells treated with 25 mM glucose (0.1% ethanol) compared to cells treated with 5 mM glucose (0.1% ethanol) for both 6 and 24 hours; expression of GPX2 was significantly increased in cells co-incubated with 25 mM glucose and VITD compared to cells treated with 25 mM glucose alone for 24 hours (Figure 2E). Finally, expression of GPX3 was also significantly decreased in cells treated with 25 mM glucose (0.1%

ethanol) compared to cells treated with 5 mM glucose (0.1% ethanol), while expression of GPX3 was notably increased in cells co-incubated with 25 mM glucose and VITD compared with cells treated with 25 mM glucose (0.1% ethanol) alone for 24 hours (Figure 2F).

We also measured SOD and CAT activities and found that cells cultured in 25 mM glucose (0.1% ethanol) had significantly decreased activities of these enzymes compared to cells cultured in 5 mM glucose (0.1% ethanol); co-treatment with VITD and 25 mM glucose significantly increased the activities of SOD and CAT compared to treatment with 25 mM glucose (0.1% ethanol) alone (Figures 3A, B). Treatment with 25 mM glucose (0.1% ethanol) also led to significantly decreased GSH and increased MDA when compared to levels recorded to treatment with 5 mM glucose (0.1% ethanol); co-exposure to VITD significantly counteracted the effects of treatment with 25 mM glucose (Figure 3C,D).

NRF2, a redox-sensitive transcription factor, can regulate expression of antioxidant genes under oxidative stress. Cells treated with 25 mM glucose (0.1% ethanol) had significantly lower NRF2 compared to cells treated with 5 mM glucose (0.1% ethanol). Co-treatment with VITD and 25 mM glucose resulted in significantly increased NRF2 compared to cells treated with 25 mM glucose (0.1% ethanol) only (Figure 3E,F).

3.3. Vitamin D mediated cytokine production in human RPE cells

The expression of IL-1 β was significantly increased in cells exposed to 25 mM glucose (0.1% ethanol) compared to cells treated with 5 mM glucose (0.1% ethanol) for both 6 and 24 hours, whereas the expression of IL-1 β was significantly reduced in cells co-treated with 25 mM glucose and VITD compared to cells treated with 25 mM glucose alone for both 6 and 24 hours (Figure 4A). Expression of IL-8 was significantly increased in cells exposed to 25 mM glucose (0.1% ethanol) compared to cells treated with 5 mM glucose (0.1% ethanol) for both 6 and 24 hours, whereas the expression of IL-8 was significantly reduced in RPE cells co-treated with 25 mM glucose and VITD compared to cells treated with 25 mM glucose (0.1% ethanol) alone for both 6 and 24 hours (Figure 4B). Similarly, the expression of TNF- α was notably increased in RPE cells treated with 25 mM glucose (0.1% ethanol) compared to cells treated with 5 mM glucose (0.1% ethanol) for both 6

and 24 hours, while the expression of TNF- α was notably decreased in cells co-exposed to 25 mM glucose and VITD compared to cells exposed to 25 mM glucose (0.1% ethanol) alone for both 6 and 24 hours (Figure 4C). Expression of VEGF-A was significantly increased in RPE cells treated with 25 mM glucose (0.1% ethanol) compared to cells treated with 5 mM glucose (0.1% ethanol) for both 6 and 24 hours, whereas VEGF-A expression was significantly decreased by in cells co-treated with 25 mM glucose and 50 nM VITD compared to cells treated with 25 mM glucose (0.1% ethanol) alone for 24 hours (Figure 4D). We also measured protein levels of secreted IL-1 β , IL-8, TNF- α and VEGF-A by ELISA and found that RPE cells cultured in media with 25 mM glucose (0.1% ethanol) for 24 hours had significantly increased levels of the above four cytokines compared to cells cultured in media with 5 mM glucose (0.1% ethanol) for the same period of time. The levels of IL-1, IL-8, TNF- and VEGFA were significantly reduced in cells co-treated with 25 mM glucose and 50 nM VITD for 24 hours compared to cells treated with 25 mM glucose (0.1% ethanol) alone for 24 hours (Figure 4E-H).

IL-33, a cytokine of the IL-1 family, is believed to have regulatory functions in inflammation and is link to metabolic diseases such as cardiovascular and diabetes [32]. Expression of IL-33 at mRNA level was significantly reduced in ARPE-19 cells exposed to 25 mM glucose (0.1% ethanol) compared to cells exposed to 5 mM glucose (0.1% ethanol) for both 6 and 24 hours (Figure 5A). Likewise, secreted IL-33 protein level was significantly decreased in cells exposed to 25 mM glucose (0.1% ethanol) compared to cells exposed to 5.0 mM glucose (0.1% ethanol) for 24 hours (Figure 5B). VITD treatment reversed high-glucose caused effects on IL-33 expression (Figure 5A,B)

3.4. Vitamin D upregulated expression of antioxidant genes in diabetic mouse retina and RPE

Initially the toxicity of VITD was assessed by treating C57BL/6 black mice with 2.5 μ g/kg of VITD or equivalent volume of corn oil (control group). The VITD toxicity assessment was based on the animal's behavior and weight change. There was no abnormal motion, activity, changes in food and water consumption or aggressive behavior observed during the period of treatment. There was no significant difference ($P = 0.48$) in weight between the VITD-treated group and the

control group (Supplementary data Figure S1), indicating that there was no VITD-associated-toxicity with the dose of 2.5 µg/kg.

The diabetic mouse retina had significantly decreased expression of catalase, Sod1, Sod2, Gpx1, Gpx2 and Gpx3 compared to control mice; VITD treatment led to a significant increase in expression of these antioxidant genes compared to untreated diabetic mice. The diabetic mouse RPE also had significantly decreased expression of catalase, Sod1, Sod2, Gpx1 and Gpx3 (though not Gpx2) when compared to the control mouse RPE; in VITD-treated diabetic mice the RPE also had a significant increase in the expression of catalase, Sod1, Sod2, Gpx1 and Gpx3 (though not Gpx2) compared to untreated diabetic mice (Figure 6).

3.5. Vitamin D regulated cytokine expression in diabetic mouse retina and RPE

Diabetic mouse retina and RPE had significantly increased mRNA levels of IL-1, IL-8 and TNF-α and VEGF-A compared to control mice. VITD treatment resulted in significantly reduced expression of these cytokine genes in both retina and RPE when compared to untreated diabetic mice (Figure 7A-D). We also measured VEGF-A protein level by ELISA and found it was significantly increased in diabetic retinas and RPE; VITD-treated retinas and RPE had lower VEGF-A compared to untreated diabetic mice (Figure 7E). We further examined IL-33 expression in control, VITD-treated and untreated diabetic mouse retinas and RPE: we found that diabetic retinas and RPE had significantly decreased IL-33 at mRNA and protein levels compared to control mice; however, IL-33 expression was significantly increased in VITD-treated retinas and RPE compared to untreated diabetic mice (Figure 7F,G).

4. Discussion

It has been suggested that VITD plays a regulatory role in different types of ocular disease [33,34]. An earlier study demonstrated that VITD deficiency was associated with DR in type 1 diabetes [17], while a recent meta-analysis found that VITD deficiency is also a risk factor for DR in type 2 diabetes [35,36]. The underlying mechanisms of VITD's association with DR are poorly understood. Our present study demonstrated that VITD treatment decreased ROS production and lipid peroxidation, enhanced antioxidant gene expression and suppressed inflammation in

high-glucose-treated cells and in the diabetic mouse model. These effects may be associated with activation of the NRF2 signal pathway, given that NRF2 expression was upregulated in VITD-treated cells and animals.

Hyperglycemia is one of the causes of increased oxidative stress in mitochondria, resulting in high production of oxygen free radicals in DR [30]. BRB dysfunction represents one of the most significant changes occurring during diabetic retinopathy. Inner and outer BRBs are formed by tight junctions between adjacent endothelial and RPE cells, respectively. The outer BRB plays many essential roles in the maintenance of normal physiological processes in the retina. Oxidative stress significantly contributes to the alteration of the outer BRB [37]. We found that high-glucose-treated RPE cells had significantly increased ROS production and lipid peroxidation, downregulated expression of antioxidant genes, decreased activities of SOD and catalase, and a lower level of GSH. VITD exposure counteracted these high-glucose-induced effects (Figures 1B, 2 and 3). Similarly, diabetic mice had a lower expression of antioxidant genes, including Catalase, Sod1, Sod2, Gpx1, 2 and 3, in retinas and in the RPE; VITD treatment significantly promoted expression of these genes (Figure 6). It has previously been reported that 3T3L1 adipocytes exposed to high glucose (25 mM) had significantly increased ROS production and NOX4 expression [38]. VITD supplementation resulted in a marked decrease in ROS production and NOX4 expression. High glucose also induced ROS generation and TXNIP expression in human retinal microvascular endothelial cells (HRMECs), while VITD treatment reversed these changes. VITD has also been shown to inhibit high-glucose-induced cell death in HRMECs and in diabetic rat retinas [39]. In the current study we detected higher Caspase 3/7 activities in RPE cells, suggesting increased cell death; again, VITD treatment reversed these effects (Figure 1C).

NRF2 is known to be the principal mediator of expression of many antioxidant genes [40]. Under physiological conditions, NRF2 activity is inhibited by binding to its substrate adapter protein, Kelch-like ECH-associated protein-1 (Keap-1), in the cytoplasm; however, in a stressed environment NRF2 is dissociated from Keap-1 via Keap-1 oxidation and translocated to the nucleus where it upregulates antioxidant gene expression by binding to the antioxidant response element

(ARE) [14]. Previous studies have demonstrated that high glucose level regulates NRF2 expression in different cell types, such as renal tubular epithelial cells and 3T3L1 adipocytes [38,41]. In the current study we found that exposure to a high glucose level decreased NRF2 expression (Figure 3E,F). VITD has been identified as a potent upregulator of NRF2 [14]. It has previously been shown that VITD ameliorated diabetic nephropathy in a rat model by activating the NRF2 signalling pathway [42]; recent work also showed that VITD functions as an anti-aging factor in rodents via activation of the same pathway [43]. In a previous study we found that VITD protected RPE cells from H₂O₂-induced damage by upregulation of NRF2 expression [24], while VITD has been shown to reverse downregulation of NRF2 expression caused by high glucose in 3T3L1 adipocytes [38]. In our current study we also found that VITD counteracted the high-glucose-induced effect on NRF2 expression (Figure 3E,F).

Inflammation as a result of hyperglycemia is another regulated process in DR. The inflammatory process in DR is modulated by augmented gene expression and the production of many proinflammatory cytokines, chemokines, complement factors and adhesion molecules. Thus, DR is regarded as an inflammatory disease [44-46]. IL-1 β has been identified as a critical determinant in the development and progression of DR [47]. It has been reported that hyperglycemia increased the gene expression and production of IL- 1 β compared to the physiological state [47]. Furthermore, there is evidence that IL-8 (also known as neutrophil chemotactic factor or chemokine 8, CXCL8) is also upregulated in the retina of diabetic patients and diabetic rabbits [48,49]. IL-8 mediates immune signaling through interaction with its two receptors CXCR-1 and CXCR-2 with high binding affinity [49], and induces the activation of p38, ERK1/2 and cJNK MAKP pathways [48]. TNF- α is another key cytokine involved in the pathogenesis of DR. It is produced by activated macrophages and its gene expression is regulated by NF-kB [34]. TNF- α modulates the inflammatory response through binding to its two receptors, TNFR-1 and TNFR-2, on target cells and triggering of the p38 MAPK and cJNK pathways [50]. Previous studies have shown that IL-1 β , IL-8 and TNF- α upregulate the expression and production of VEGF in diabetic animal models, resulting in a substantial decrease of retinal pericytes, marked capillary

deterioration and breakdown of the blood-retinal barrier [44]. The expression and activity of VEGF have also been reported to be upregulated in diabetic patients' samples, high-glucose-treated cells and in STZ-induced diabetic animal models [51,52]. Our current data from *in vitro* and *in vivo* experiments have shown that the expression of IL-1 β , IL-8, TNF- α , and VEGF was substantially increased in ARPE-19 cells treated with high glucose and in the retinas of STZ-induced diabetic mice compared to control groups; furthermore, the gene expression of these cytokines in both experimental models was notably repressed following VITD treatment (Figures 4, 7).

There is evidence to suggest that IL-33 can play a protective role in obesity, cardiovascular diseases and diabetes [53,54]. Recent studies showed that IL-33 treatment slowed down disease progression of type 1 diabetes in mice, mainly via participation of CD4⁺Foxp3⁺ regulatory T cells (Tregs) [55,56]. IL-33 expression has also been reported to be downregulated in diabetic patients and in STZ-induced diabetic mice [57-59]. Previous reports have demonstrated that IL-33 is expressed in RPE cells and in mouse brain and retina [24,60]. Our present data demonstrated that IL-33 was notably decreased at mRNA and protein levels in ARPE-19 cells incubated with high glucose and in the retinas and RPE of STZ-induced diabetic mice; however, IL-33 expression was notably increased following VITD treatment in both experimental models (Figures 5 and 7F,G).

In summary, our present study demonstrates that VITD has a protective role against high-glucose-induced oxidative damage and inflammation in retina and RPE, suggesting VITD as a potential therapeutic agent for diabetic retinopathy.

Author Contributions X.S. developed the concept. A.M.T., M.A., R.H.A., L.B., X.Z. performed the experiments. A.M.T. and X.S. analyzed the data. J.R., Z.Z. and X.S. drafted the manuscript.

Funding: This study was supported by a PhD scholarship from Saudi Arabia Government, the Rosetrees Trust (M160, M160-F1, M160-F2) and National Eye Research Centre (SAC037). Dr Shu's visiting to Changsha University was supported by the Overseas Teacher Program, Department of Education, Hunan Province, P. R. China (2019024).

Conflicts of Interest: No conflict of interest needs to be declared.

References

- 400 [1] Safi, S.Z., Qvist, R., Kumar, S., Batumalaie, K. and Ismail, I.S.B., 2014. Molecular mechanisms of
401 diabetic retinopathy, general preventive strategies, and novel therapeutic targets. *BioMed*
402 *research international*, 2014, pp. 801269.
- 403 [2] Williams, R., Airey, M., Baxter, H., Forrester, J.K.M., Kennedy-Martin, T. and Girach, A., 2004.
404 Epidemiology of diabetic retinopathy and macular oedema: a systematic review. *Eye*, 18(10),
405 pp.963-983.
- 406 [3] Yau, J.W., Rogers, S.L., Kawasaki, R., Lamoureux, E.L., Kowalski, J.W., Bek, T., Chen, S.J., Dekker,
407 J.M., Fletcher, A., Grauslund, J. and Haffner, S., 2012. Global prevalence and major risk factors
408 of diabetic retinopathy. *Diabetes care*, 35(3), pp.556-564.
- 409 [4] Matteucci, A., Varano, M., Mallozzi, C., Gaddini, L., Villa, M., Gabrielli, S., Formisano, G., Pricci,
410 F. and Malchiodi-Albedi, F., 2015. Primary retinal cultures as a tool for modeling diabetic
411 retinopathy: an overview. *BioMed research international*, 2015, pp.364924.
- 412 [5] Ola, M.S., Nawaz, M.I., Siddiquei, M.M., Al-Amro, S. and El-Asrar, A.M.A., 2012. Recent
413 advances in understanding the biochemical and molecular mechanism of diabetic
414 retinopathy. *Journal of diabetes and its complications*, 26(1), pp.56-64.
- 415 [6] Rivera, J.C., Dabouz, R., Noueihed, B., Omri, S., Tahiri, H. and Chemtob, S., 2017. Ischemic
416 retinopathies: oxidative stress and inflammation. *Oxidative medicine and cellular*
417 *longevity*, 2017, pp.3940241.
- 418 [7] Stitt, A.W., Curtis, T.M., Chen, M., Medina, R.J., McKay, G.J., Jenkins, A., Gardiner, T.A., Lyons,
419 T.J., Hammes, H.P., Simo, R. and Lois, N., 2016. The progress in understanding and treatment
420 of diabetic retinopathy. *Progress in retinal and eye research*, 51, pp.156-186.
- 421 [8] Platania, C.B.M., Leggio, G.M., Drago, F., Salomone, S. and Bucolo, C., 2018. Computational
422 systems biology approach to identify novel pharmacological targets for diabetic
423 retinopathy. *Biochemical pharmacology*, 158, pp.13-26.
- 424 [9] Lazzara, F., Fidilio, A., Platania, C.B.M., Giurdanella, G., Salomone, S., Leggio, G.M., Tarallo, V.,
425 Cicatiello, V., De Falco, S., Eandi, C.M. and Drago, F., 2019. Aflibercept regulates retinal

inflammation elicited by high glucose via the PIGF/ERK pathway. *Biochemical pharmacology*, 168, pp.341-351.

[10] Platania, C.B.M., Lazzara, F., Fidilio, A., Fresta, C.G., Conti, F., Giurdanella, G., Leggio, G.M., Salomone, S., Drago, F. and Bucolo, C., 2019. Blood-retinal barrier protection against high glucose damage: The role of P2X7 receptor. *Biochemical pharmacology*, 168, pp.249-258.

[11] D'Amico, A.G., Maugeri, G., Reitano, R., Bucolo, C., Saccone, S., Drago, F. and D'Agata, V., 2015. PACAP modulates expression of hypoxia-inducible factors in streptozotocin-induced diabetic rat retina. *Journal of Molecular Neuroscience*, 57(4), pp.501-509.

[12] Platania, C.B.M., Maisto, R., Trotta, M.C., D'Amico, M., Rossi, S., Gesualdo, C., D'Amico, G., Balta, C., Herman, H., Hermenean, A. and Ferraraccio, F., 2019. Retinal and circulating mi RNA expression patterns in diabetic retinopathy: An in silico and in vivo approach. *British journal of pharmacology*, 176(13), pp.2179-2194.

[13] Bikle, D.D., 2014. Vitamin D metabolism, mechanism of action, and clinical applications. *Chemistry & biology*, 21(3), pp.319-329.

[14] Berridge, M.J., 2015. Vitamin D: a custodian of cell signalling stability in health and disease. *Biochemical Society Transactions*, 43(3), pp.349-358.

[15] Ashinne, B., Rajalakshmi, R., Anjana, R.M., Narayan, K.V., Jayashri, R., Mohan, V. and Hendrick, A.M., 2018. Association of serum vitamin D levels and diabetic retinopathy in Asian Indians with type 2 diabetes. *Diabetes research and clinical practice*, 139, pp.308-313.

[16] Bener, A., Eliaçık, M., Cincik, H., Öztürk, M., DeFronzo, R.A. and Abdul-Ghani, M., 2018. The impact of vitamin D deficiency on retinopathy and hearing loss among Type 2 diabetic patients. *BioMed research international*, 2018, pp.2714590

[17]. Kaur, H., Donaghue, K.C., Chan, A.K., Benitez-Aguirre, P., Hing, S., Lloyd, M., Cusumano, J., Pryke, A. and Craig, M.E., 2011. Vitamin D deficiency is associated with retinopathy in children and adolescents with type 1 diabetes. *Diabetes care*, 34(6), pp.1400-1402.

451 [18] Aksoy, H., Akçay, F., Kurtul, N., Baykal, O. and Avci, B., 2000. Serum 1, 25 dihydroxy vitamin D
452 (1, 25 (OH) 2D3), 25 hydroxy vitamin D (25 (OH) D) and parathormone levels in diabetic
453 retinopathy. *Clinical biochemistry*, 33(1), pp.47-51.

454 [19] Payne, J., Ray, R., Watson, D., Delille, C., Rimler, E., Cleveland, J., Lynn, M., Tangpricha, V. and
455 Srivastava, S., 2012. Vitamin D insufficiency in diabetic retinopathy. *Endocrine Practice*, 18(2),
456 pp.185-193.

457 [20] Bućan, K., Ivanišević, M., Zemunik, T., Boraska, V., Škrabić, V., Vatauvuk, Z., Galetović, D. and
458 Znaor, L., 2009. Retinopathy and nephropathy in type 1 diabetic patients—association with
459 polymorphisms of vitamin D-receptor, TNF, Neuro-D and IL-1 receptor 1 genes. *Collegium
460 antropologicum*, 33(2), pp.99-105.

461 [21] Taverna, M.J., Sola, A., Guyot-Argenton, C., Pacher, N., Bruzzo, F., Slama, G., Reach, G. and
462 Selam, J.L., 2002. Taq I polymorphism of the vitamin D receptor and risk of severe diabetic
463 retinopathy. *Diabetologia*, 45(3), pp.436-442.

464 [22] Taverna, M.J., Selam, J.L. and Slama, G., 2005. Association between a protein polymorphism in
465 the start codon of the vitamin D receptor gene and severe diabetic retinopathy in
466 C-peptide-negative type 1 diabetes. *The Journal of Clinical Endocrinology &
467 Metabolism*, 90(8), pp.4803-4808.

468 [23] Tohari, A.M., Zhou, X. and Shu, X., 2016. Protection against oxidative stress by vitamin D in
469 cone cells. *Cell biochemistry and function*, 34(2), pp.82-94.

470 [24] Tohari, A.M., Alhasani, R.H., Biswas, L., Patnaik, S.R., Reilly, J., Zeng, Z. and Shu, X., 2019.
471 Vitamin D Attenuates Oxidative Damage and Inflammation in Retinal Pigment Epithelial
472 Cells. *Antioxidants*, 8(9), p.341.

473 [25] Albert, D.M., Scheef, E.A., Wang, S., Mehraein, F., Darjatmoko, S.R., Sorenson, C.M. and
474 Sheibani, N., 2007. Calcitriol is a potent inhibitor of retinal neovascularization. *Investigative
475 ophthalmology & visual science*, 48(5), pp.2327-2334.

476 [26] Mantell, D.J., Owens, P.E., Bundred, N.J., Mawer, E.B. and Canfield, A.E., 2000. 1α ,
477 25-dihydroxyvitamin D3 inhibits angiogenesis in vitro and in vivo. *Circulation research*, 87(3),
478 pp.214-220.

479 [27] Ramakrishnan, V., Yang, Q.J., Quach, H.P., Cao, Y., Chow, E.C., Mager, D.E. and Pang, K.S.,
480 2016. Physiologically-based pharmacokinetic-pharmacodynamic modeling of 1α ,
481 25-dihydroxyvitamin D3 in mice. *Drug Metabolism and Disposition*, 44(2), pp.189-208.

482 [28] Feit-Leichman, R.A., Kinouchi, R., Takeda, M., Fan, Z., Mohr, S., Kern, T.S. and Chen, D.F., 2005.
483 Vascular damage in a mouse model of diabetic retinopathy: relation to neuronal and glial
484 changes. *Investigative ophthalmology & visual science*, 46(11), pp.4281-4287.

485 [29] Talahalli, R., Zarini, S., Sheibani, N., Murphy, R.C. and Gubitosi-Klug, R.A., 2010. Increased
486 synthesis of leukotrienes in the mouse model of diabetic retinopathy. *Investigative*
487 *ophthalmology & visual science*, 51(3), pp.1699-1708.

488 [30] Wu, M.Y., Yiang, G.T., Lai, T.T. and Li, C.J., 2018. The oxidative stress and mitochondrial
489 dysfunction during the pathogenesis of diabetic retinopathy. *Oxidative medicine and cellular*
490 *longevity*, 2018, pp.3420187.

491 [31] Redza-Dutordoir, M. and Averill-Bates, D.A., 2016. Activation of apoptosis signalling pathways
492 by reactive oxygen species. *Biochimica et Biophysica Acta (BBA)-Molecular Cell*
493 *Research*, 1863(12), pp.2977-2992.

494 [32] Altara, R., Ghali, R., Mallat, Z., Cataliotti, A., Booz, G.W. and Zouein, F.A., 2018. Conflicting
495 vascular and metabolic impact of the IL-33/sST2 axis. *Cardiovascular research*, 114(12),
496 pp.1578-1594.

497 [33] Nebbioso, M., Buomprisco, G., Pascarella, A. and Pescosolido, N., 2017. Modulatory effects of
498 $1, 25$ -dihydroxyvitamin D3 on eye disorders: A critical review. *Critical reviews in food science*
499 *and nutrition*, 57(3), pp.559-565.

500 [34] Reins, R.Y. and McDermott, A.M., 2015. Vitamin D: implications for ocular disease and
501 therapeutic potential. *Experimental eye research*, 134, pp.101-110.

502 [35] Luo, B.A., Gao, F. and Qin, L.L., 2017. The association between vitamin D deficiency and
503 diabetic retinopathy in type 2 diabetes: a meta-analysis of observational
504 studies. *Nutrients*, 9(3), p.307.

505 [36] Zhang, J., Upala, S. and Sanguankee, A., 2017. Relationship between vitamin D deficiency and
506 diabetic retinopathy: a meta-analysis. *Canadian Journal of Ophthalmology*, 52, pp.S39-S44.

507 [37] Bucolo, C., Drago, F., Lin, L.R., Reddy, V.N., 2006. Sigma receptor ligands protect human retinal
508 cells against oxidative stress. *Neuroreport*, 17(3), pp.287-291.

509 [38] Manna, P., Achari, A.E. and Jain, S.K., 2017. Vitamin D supplementation inhibits oxidative
510 stress and upregulate SIRT1/AMPK/GLUT4 cascade in high glucose-treated 3T3L1 adipocytes
511 and in adipose tissue of high fat diet-fed diabetic mice. *Archives of biochemistry and*
512 *biophysics*, 615, pp.22-34.

513 [39] Lu, L., Lu, Q., Chen, W., Li, J., Li, C. and Zheng, Z., 2018. Vitamin D3 protects against diabetic
514 retinopathy by inhibiting high-glucose-induced activation of the ROS/TXNIP/NLRP3
515 inflammasome pathway. *Journal of diabetes research*, 2018, pp.8193523.

516 [40] Loboda, A., Damulewicz, M., Pyza, E., Jozkowicz, A. and Dulak, J., 2016. Role of Nrf2/HO-1
517 system in development, oxidative stress response and diseases: an evolutionarily conserved
518 mechanism. *Cellular and molecular life sciences*, 73(17), pp.3221-3247.

519 [41] Zhang, J., Zhao, X., Zhu, H., Wang, J., Ma, J. and Gu, M., 2019. Apigenin Protects Against Renal
520 Tubular Epithelial Cell Injury and Oxidative Stress by High Glucose via Regulation of
521 NF-E2-Related Factor 2 (Nrf2) Pathway. *Medical science monitor: international medical*
522 *journal of experimental and clinical research*, 25, p.5280.

523 [42] Nakai, K., Fujii, H., Kono, K., Goto, S., Kitazawa, R., Kitazawa, S., Hirata, M., Shinohara, M.,
524 Fukagawa, M. and Nishi, S., 2014. Vitamin D activates the Nrf2-Keap1 antioxidant pathway
525 and ameliorates nephropathy in diabetic rats. *American journal of hypertension*, 27(4),
526 pp.586-595.

527 [43] Chen, L., Yang, R., Qiao, W., Zhang, W., Chen, J., Mao, L., Goltzman, D. and Miao, D., 2019. 1,
528 25-Dihydroxyvitamin D exerts an antiaging role by activation of Nrf2-antioxidant signaling and
529 inactivation of p16/p53-senescence signaling. *Aging cell*, 18(3), p.e12951.

530 [44] Semeraro, F., Cancarini, A., Rezzola, S., Romano, M.R. and Costagliola, C., 2015. Diabetic
531 retinopathy: vascular and inflammatory disease. *Journal of diabetes research*, 2015,
532 pp.582060.

533 [45] Wang, J., Yang, M.M., Li, Y.B., Liu, G.D., Teng, Y. and Liu, X.M., 2013. Association of CFH and
534 CFB gene polymorphisms with retinopathy in type 2 diabetic patients. *Mediators of*
535 *inflammation*, 2013, pp.748435.

536 [46] Gologorsky, D., Thanos, A. and Vavvas, D., 2012. Therapeutic interventions against
537 inflammatory and angiogenic mediators in proliferative diabetic retinopathy. *Mediators of*
538 *inflammation*, 2012, pp.629452.

539 [47] Kowluru, R.A. and Odenbach, S., 2004. Effect of long-term administration of α -lipoic acid on
540 retinal capillary cell death and the development of retinopathy in diabetic
541 rats. *Diabetes*, 53(12), pp.3233-3238.

542 [48] Liu, X., Ye, F., Xiong, H., Hu, D., Limb, G.A., Xie, T., Peng, L., Yang, W., Sun, Y., Zhou, M. and
543 Song, E., 2014. IL-1 β upregulates IL-8 production in human Müller cells through activation of
544 the p38 MAPK and ERK1/2 signaling pathways. *Inflammation*, 37(5), pp.1486-1495.

545 [49] Goczalik, I., Ulbricht, E., Hollborn, M., Raap, M., Uhlmann, S., Weick, M., Pannicke, T.,
546 Wiedemann, P., Bringmann, A., Reichenbach, A. and Francke, M., 2008. Expression of CXCL8,
547 CXCR1, and CXCR2 in neurons and glial cells of the human and rabbit retina. *Investigative*
548 *ophthalmology & visual science*, 49(10), pp.4578-4589.

549 [50] Kim, E.K. and Choi, E.J., 2010. Pathological roles of MAPK signaling pathways in human
550 diseases. *Biochimica et Biophysica Acta (BBA)-Molecular Basis of Disease*, 1802(4),
551 pp.396-405.

552 [51] Wang, J., Xu, X., Elliott, M.H., Zhu, M. and Le, Y.Z., 2010. Müller cell-derived VEGF is essential
553 for diabetes-induced retinal inflammation and vascular leakage. *Diabetes*, 59(9),
554 pp.2297-2305.

555 [52] Yuan, Z., Feng, W., Hong, J., Zheng, Q., Shuai, J. and Ge, Y., 2009. p38MAPK and ERK promote
556 nitric oxide production in cultured human retinal pigmented epithelial cells induced by high
557 concentration glucose. *Nitric oxide*, 20(1), pp.9-15.

558 [53] Miller, A.M., Xu, D., Asquith, D.L., Denby, L., Li, Y., Sattar, N., Baker, A.H., McInnes, I.B. and
559 Liew, F.Y., 2008. IL-33 reduces the development of atherosclerosis. *The Journal of*
560 *experimental medicine*, 205(2), pp.339-346.

561 [54] Miller, A.M., Asquith, D.L., Hueber, A.J., Anderson, L.A., Holmes, W.M., McKenzie, A.N., Xu, D.,
562 Sattar, N., McInnes, I.B. and Liew, F.Y., 2010. Interleukin-33 induces protective effects in
563 adipose tissue inflammation during obesity in mice. *Circulation research*, 107(5), pp.650-658.

564 [55] Lu, J., Liang, Y., Zhao, J., Meng, H. and Zhang, X., 2019. Interleukin-33 prevents the
565 development of autoimmune diabetes in NOD mice. *International immunopharmacology*, 70,
566 pp.9-15.

567 [56] Pavlovic, S., Petrovic, I., Jovicic, N., Ljujic, B., Miletic Kovacevic, M., Arsenijevic, N. and Lukic,
568 M.L., 2018. IL-33 prevents MLD-STZ induction of diabetes and attenuate insulinitis in
569 prediabetic NOD mice. *Frontiers in immunology*, 9, p.2646.

570 [57] Anand, G., Vasanthakumar, R., Mohan, V., Babu, S. and Aravindhan, V., 2014. Increased IL-12
571 and decreased IL-33 serum levels are associated with increased Th1 and suppressed Th2
572 cytokine profile in patients with diabetic nephropathy (CURES-134). *International journal of*
573 *clinical and experimental pathology*, 7(11), p.8008.

574 [58] Miller, A.M., Purves, D., McConnachie, A., Asquith, D.L., Batty, G.D., Burns, H., Cavanagh, J.,
575 Ford, I., McLean, J.S., Packard, C.J. and Shiels, P.G., 2012. Soluble ST2 associates with diabetes
576 but not established cardiovascular risk factors: a new inflammatory pathway of relevance to
577 diabetes?. *PloS one*, 7(10), pp.e47830

[59] Rui, T., Zhang, J., Xu, X., Yao, Y., Kao, R. and Martin, C.M., 2012. Reduction in IL-33 expression exaggerates ischaemia/reperfusion-induced myocardial injury in mice with diabetes mellitus. *Cardiovascular research*, 94(2), pp.370-378.

[60] Wicher, G., Husic, E., Nilsson, G. and Forsberg-Nilsson, K., 2013. Developmental expression of IL-33 in the mouse brain. *Neuroscience letters*, 555, pp.171-176.

606

607 **Figure 1.** (A) ARPE-19 cell viability. Cells treated with 5mM glucose, 25 mM glucose or a
608 combination of 25mM glucose and VITD (50 nM) for 6 and 24 hours. Cell viability was measured
609 using the MTT assay described. (B) VITD treatment can protect against ROS production in cells
610 exposed to a high level of glucose. Cells were treated with or without VITD (50 nM) for 6 and 24
611 hours, ROS was measured. (C) VITD treatment can protect against apoptosis in cells treated with a
612 high concentration of glucose. Cells were treated with or without VITD (50 nM) and activities of
613 Caspase 3/7, a biomarker for apoptosis, were measured. Data were analysed with non-parametric

614 Kruskal-wallis followed by Dunn's multiple comparison test (n=5). Φ $p < 0.05$, 5 mM Glucose +
615 VITD vs. 5 mM Glucose; $*p < 0.05$, 25 mM Glucose vs. 5 mM Glucose; $\#p < 0.05$, 25mM Glucose +
616 VITD vs. 25 mM glucose; $\#\#p < 0.01$, 25mM Glucose+VITD vs. 25 mM glucose. NS, 5 mM glucose +
617 VITD vs. 5 mM glucose.

619 **Figure 2.** VITD treatment can enhance the expression of antioxidants genes in ARPE-19 cells
620 challenged with a high level of glucose. Cells were treated with or without VITD (50 nM) for 6 and
621 24 hours. the expression of the antioxidant genes catalase (A), SOD1 (B), SOD2 (C), GPX1 (D), GPX2
622 (E) and GPX3 (F) was measured using qRT-PCR assay. Data were analysed with non-parametric
623 Kruskal-wallis followed by Dunn's multiple comparison test (n=5). * $p < 0.05$, 25 mM Glucose vs.
624 5 mM Glucose; # $p < 0.05$, 25mM Glucose + VITD vs. 25 mM glucose. NS in Figure 2D, 25
625 mM Glucose vs. 5 mM Glucose or 25mM Glucose + VITD vs. 25 mM glucose; NS in Figure
626 2E and F, 25mM Glucose + VITD vs. 25 mM glucose.
627
628

Figure 3. VITD treatment increased antioxidant capacity. Cells were treated with or without VITD (50 nM) for 24 hours. Activities of superoxide dismutase (SOD) (A) and catalase (CAT) (B) and levels of glutathione (GSH) (C) and malondialdehyde (MDA) (D) were measured using commercial kits. NRF2 protein detected in control and treated cells was examined by Western blotting (E). NRF2 protein levels were quantified by normalizing with GAPDH protein (F). Data

635 were analysed with non-parametric Kruskal-wallis followed by Dunn's multiple
636 comparison test (n=4). $*p < 0.05$, 25 mM Glucose vs. 5 mM Glucose; $**p < 0.01$, 25 mM
637 Glucose vs. 5 mM Glucose; $###p < 0.01$, 25mM Glucose+VITD vs. 25 mM glucose.

Figure 4. VITD regulated the expression of pro-inflammatory cytokines in ARPE-19 cells treated with high glucose or co-treated with high glucose and VITD (50 nM) for 6 and 24 hours. The relative expression of IL-1 β (A), IL-8 (B), TNF- α (C) and VEGF (D) was determined by qRT-PCR assay. Secreted protein levels of IL-1 β (E), IL-8 (F), TNF- α (G) and VEGF (H) were measured by ELISA. Data were analysed with non-parametric Kruskal-wallis followed by Dunn's multiple comparison test (n=4). * p <0.05, 25 mM Glucose vs. 5 mM Glucose; ** p <0.01, 25 mM Glucose vs. 5 mM Glucose; # p <0.05, 25mM Glucose+VITD vs. 25 mM glucose.

Figure 5. The expression of IL-33 in stressed ARPE-19 cells. (A) The relative expression of IL-33 as determined by qRT-PCR assay in ARPE-19 cells treated for 6 and 24 hours with 5 mM glucose, with 25 mM glucose, or co-treated with 25 mM glucose and VITD (50 nM). (B) Secreted IL-33 protein levels in media of cells treated with or without VITD (50 nM) for 24 hours were measured by ELISA. Data were analysed with non-parametric Kruskal-wallis followed by Dunn's multiple comparison test (n=4). Φ $p < 0.05$, 5 mM Glucose + VITD vs. 5 mM Glucose; * $p < 0.05$, 25 mM Glucose vs. 5 mM Glucose; ** $p < 0.01$, 25 mM Glucose vs. 5 mM glucose. # $p < 0.05$, 25 mM Glucose + VITD vs. 25 mM glucose.

677 **Figure 6.** Effect of VITD on antioxidant gene expression in diabetic retinas and RPE. Retinas
678 and RPE were dissected from control, diabetic and VITD-treated mice (described in section
679 2.7). RNA was extracted and cDNA was synthesized. Relative expression of antioxidant genes:
680 catalase (MCAT) (A), SOD1 (B), SOD2 (C), GPX1 (D), GPX2 (E) and GPX3 (F) in the retina (RET)
681 and RPE was examined by qRT-PCR. Data were analysed with non-parametric
682 Kruskal-wallis followed by Dunn's multiple comparison test (n=6 samples in each group). * p
683 <0.05, diabetic vs. control; # p <0.05, diabetic + VITD vs. diabetic. NS, diabetic vs. control or
684 diabetic + VITD vs. diabetic.
685

Figure 7. Effect of VITD on proinflammatory gene expression in diabetic retinas and RPE.

Retinas and RPE were dissected from control, diabetic and VITD-treated mice (described in section 2.7). RNA was extracted and cDNA was synthesized. Relative expression of inflammatory cytokines IL-1 β (A), IL-8 (B), TNF α (C), VEGF (D) and IL-33 (F) in retina (RET) and RPE was examined by qRT-PCR. Protein levels of VEGF (E) and IL-33 (G) were measured by ELISA. Data were analysed with non-parametric Kruskal-wallis followed by Dunn's multiple comparison test (n=6 samples in each group). * p <0.05, diabetic vs. control; ** p <0.01, diabetic vs. control; # p <0.05, diabetic + VITD vs. diabetic.