d-penicillamine prevents ram sperm agglutination by reducing the disulphide bonds of a copper-binding sperm protein

T Leahy¹, JP Rickard¹, RJ Aitken² and SP de Graaf¹

¹Faculty of Veterinary Science, The University of Sydney, Camperdown, New South Wales, Australia and ²Discipline of Biological Sciences, Faculty of Science and IT and Faculty of Health and Medicine, University of Newcastle, Callaghan, New South Wales, Australia

Correspondence should be addressed to T Leahy; Email: tamara.leahy@sydney.edu.au

Abstract

Head-to-head agglutination of ram spermatozoa is induced by dilution in the Tyrode's capacitation medium with albumin, lactate and pyruvate (TALP) and ameliorated by the addition of the thiol d-penicillamine (PEN). To better understand the association and disassociation of ram spermatozoa, we investigated the mechanism of action of PEN in perturbing sperm agglutination. PEN acts as a chelator of heavy metals, an antioxidant and a reducing agent. Chelation is not the main mechanism of action, as the broad-spectrum chelator ethylenediaminetetraacetic acid and the copper-specific chelator bathocuproinedisulfonic acid were inferior anti-agglutination agents compared with PEN. Oxidative stress is also an unlikely mechanism of sperm association, as PEN was significantly more effective in ameliorating agglutination than the antioxidants superoxide dismutase, ascorbic acid, a-tocopherol and catalase. Only the reducing agents cysteine and dL-dithiothreitol displayed similar levels of non-agglutinated spermatozoa at 0 h compared with PEN but were less effective after 3 h of incubation (37 °C). The addition of 10 μM Cu²⁺ to 250 μM PEN + TALP caused a rapid reversion of the motile sperm population from a non-agglutinated state to an agglutinated state. Other heavy metals (cobalt, iron, manganese and zinc) did not provoke such a strong response. Together, these results indicate that PEN prevents sperm association by the reduction of disulphide bonds on a sperm membrane protein that binds copper. ADAM proteins are possible candidates, as targeted inhibition of the metalloproteinase domain significantly increased the percentage of motile, non-agglutinated spermatozoa (52.0% ± 7.8) compared with TALP alone (10.6% ± 6.1).

Introduction

We have previously shown that the extension of ram spermatozoa in the commonly used Tyrode's capacitation medium with albumin, lactate and pyruvate (TALP) causes rapid head-to-head sperm agglutination in a highly specific and persistent manner (Leahy et al. 2016). Ram sperm aggregation in TALP does not coincide with a loss of sperm function, as often seen after spermatozoa are exposed to physicochemical stressors such as high dilution or washing, cold shock, and extreme pH or osmotic conditions (Mann 1964). Agglutinated sperm retain their motility, and the phenomenon appears similar to the agglutination that occurs when sera (e.g. follicular fluid and plasma) are added to in vitro fertilisation (IVF) media to stimulate cholesterol efflux of ram spermatozoa (Ehrenwald et al. 1990, Funahashi & Day 1993). It is uncertain whether this phenomenon is physiologically relevant or an artefact of in vitro sperm manipulation; however, agglutination of rabbit spermatozoa has been noted after placement in the doe uterine lumen (Brown & Senger 1982).

Ram spermatozoa require serum for IVF (Huneau et al. 1994, Li et al. 2006), as TALP medium alone does not stimulate protein tyrosine phosphorylation and cholesterol efflux in this species (Colas et al. 2008, Leahy & Gadella 2015, Leahy et al. 2016). Therefore, it is important to understand what factors are driving ram sperm association and disassociation, as it commonly occurs during ram sperm IVF. We have previously shown that the thiol d-penicillamine (PEN) is highly effective in preventing or reversing sperm association in TALP (Leahy et al. 2016). The effect of PEN was immediate, long-lasting and had no effect on total motility or the ability of spermatozoa to undergo capacitation. These characteristics make this compound well suited for in vitro use in sperm-handling protocols to counteract agglutination issues.
Penicillamine was named so because it is a degradation product of penicillin that contains an amine group (Fig. 1) (Abrahams et al. 1943). Penicillamine (PEN) also contains two other functional groups, a carboxyl and a sulphydryl (Fig. 1). Although it possesses no antibacterial properties, these functional groups impart a range of biochemical behaviours that have been therapeutically exploited for more than 50 years to treat copper toxicities (Walshe 1956). The sulphydryl group is of greatest biological significance, as it can combine with a multitude of compounds and act as a chelator or antioxidant as well as a participant in redox reactions as a reducing agent (Netter et al. 1987). In this study, we investigate how PEN perturbs sperm agglutination to shed some light on the factors involved in autologous sperm binding.

Materials and methods

Chemicals

Unless otherwise stated, products were sourced from Sigma-Aldrich and were of the highest reagent grade available. The base medium used was modified Tyrode’s medium supplemented with albumin, lactate and pyruvate (TALP) (Parrish et al. 1988), which consisted of 2 mM CaCl₂, 3.1 mM KCl, 0.4 mM MgCl₂, 95 mM NaCl, 0.3 mM NaH₂PO₄, 10 mM HEPES, 21.6 mM Na lactate, 5 mM glucose, 1 mM Na pyruvate, 25 mM NaHCO₃, 0.03 mM phenol red and 3 mg/ml BSA (fatty acid free). The final pH and osmolarity of the various diluents was 7.4 and 300–310 mOsm/L respectively.

Sperm preparation

Ram semen was collected from two Merino rams and one Merino cross ram (n = 3) using an artificial vagina with project approval from the University of Sydney’s Animal Ethics Committee (Protocol No: 2013/5854). Two ejaculates were collected from each ram, three times a week. Only ejaculates that had a wave motion score of 4 (out of 5) or higher were used. Spermatozoa were diluted to 50 × 10⁶ spermatozoa/mL in 1 mL aliquots and held for 3 h in an Eppendorf tube in a humidified incubator set at 38.5 °C in an atmosphere of 5% CO₂.

Figure 1 Structure of α-penicillamine.

Experiment design

Each experiment was replicated six times using two ejaculates from three Merino rams. Motility and agglutination were assessed immediately following sperm dilution (0 h) and after 3 h of incubation. Except in Experiment 7, all compounds of interest were added to TALP at the desired concentration and then the sperm samples were diluted to 50 × 10⁶ spermatozoa/mL.

Experiment 1. As PEN is an effective copper chelator, the influence of copper ions (Cu²⁺) on sperm agglutination in TALP was assessed. A dose course of copper sulphate (0–500 µM) was added to TALP supplemented with 250 µM PEN.

Experiment 2. Experiment 2 assessed the specificity of the effect of copper on inducing sperm agglutination by comparing it to a range of other heavy metals. A standard dose of 10 µM of the following metals was added to TALP supplemented with 250 µM PEN: iron sulphate heptahydrate, zinc sulphate heptahydrate, manganese sulphate monohydrate, cobalt sulphate heptahydrate and copper sulphate.

Experiment 3. A Cu²⁺-dependent lectin associated with agglutination of goat spermatozoa has been described (Roy et al. 2014). The lectin was sialic acid-specific and agglutinated cells could be dissociated with neutralised sialic acid (Roy et al. 2014). The aim of Experiment 3 was to assess the response of 0, 1, 10, 20 or 30 mM N-acetylneuraminic acid (sialic acid; Cayman Chemicals) on TALP-induced ram sperm agglutination.

Penicillamine (PEN) can act as a chelator, an antioxidant and a reducing agent. Experiments 4–6 were designed to compare the ability of TALP to reduce agglutination of ram spermatozoa in TALP with that of other chelators, antioxidants and reducing agents.

Experiment 4. Experiment 4 compared the effects of the broad-scale chelator, ethylenediaminetetraacetic acid disodium salt (EDTA) and the copper-specific chelator bathocuproinedisulfonic acid disodium salt (BCS) to PEN. To broaden the basis for comparisons between the effects of each substance studied, standardised low (0.1 mM) and high (1 mM) concentrations were tested.

Experiment 5. Experiment 5 compared the effects of four antioxidants to PEN (1 mM), l-ascorbic acid (VIT C; 1 mg/mL) was supplemented at the physiological concentration in ram semen (Mann 1964). Superoxide dismutase (SOD; 800 IU mL⁻¹), catalase (150 IU mL⁻¹) and α-tocopherol (VIT E; 1 mM; solubilised in ethanol with a final concentration of 0.5% (v/v)) were supplemented at levels that were previously shown to counteract sperm oxidative stress in vitro (Aitken & Clarkson 1988, Maxwell & Stojanov 1996, Leahy et al. 2010).

Experiment 6. Experiment 6 compared the reducing agents, reduced l-glutathione (GSH), l-cysteine (CYS) and dl-dithiothreitol (DTT) to PEN. To broaden the basis for comparisons between the effects of each substance studied, standardised low (0.1 mM) and high (1 mM) concentrations were tested.

Experiment 7. ADAM (A disintegrin and metalloproteinase) proteins are involved in cell adhesion, are abundant on the extracellular sperm membrane (Loechel & Wewer 2001, Byrne et al. 2012) and may be activated by copper (Loechel & Wewer 2001). The aim of Experiment 7 was to assess the effect of targeting either the “integrin” or the “metallopeinase”
functions of ADAM proteins through the addition of a
RGDS sequence blocking peptide (0.1 and 1 mM; In vitro
technologies, Lane Cove West, NSW, Australia) or the ADAM
metalloproteinase inhibitor tumour necrosis factor-β protease
inhibitor-2 (TAPI-2, 25 µM; Sapphire Bioscience, Waterloo,
NSW, Australia) respectively. The dose of TAPI-2 (Tousseyn
et al. 2009) and RGDS peptide (Mould et al. 1991) utilised
were based on the studies on somatic cells that showed
physiological responses in these concentration ranges. Only
in Experiment 7, samples were pre-incubated with various
treatments at 500 × 10^6 spermatozoa/mL for 15 min at 37 °C in
PBS and then diluted to 50 × 10^6 spermatozoa/mL in TALP
supplemented with the same treatments.

**Sperm auto-agglutination assay**

Spermatozoa were observed under light microscopy using
phase-contrast optics (400 × magnification) with an Olympus
BX51 microscope equipped with an Olympus DP73 digital
camera. Four fields of view were recorded over 1 min. Sam-
ples were randomised and coded, so the assessor was blind to
sample treatment. The videos were watched frame by frame
using the Olympus cellSens imaging software. Spermatozoa
(200 cells counted per sample) were assigned to one of four
categories: motile and non-agglutinated, motile and aggluti-
nated, non-motile and non-agglutinated, or non-motile and
agglutinated.

**Statistical analysis**

Statistical analysis was performed using linear mixed model
regression in GENSTAT (version 16; VSN International, Hemel
Hempstead, UK). Interactions between treatment effects and
time were assessed with ejaculate and ram incorporated into
the blocking structure. Data are presented as the model-
derived mean ± standard error of the mean (s.e.m) of six repli-
cates. Results are expressed as significant (*P < 0.05) and highly
significant (**P < 0.001) compared with control samples.

**Results**

**Low concentrations of cupric ions cause mass
agglutination of motile spermatozoa**

TALP was supplemented with 250 µM PEN to produce a
non-agglutinated, control population (Fig. 2A & Supple-
mental Video 1; control, representative sample at 0 h).
Supplementation of 10 µM (Fig. 2B & Supplementary
Video 2; copper, representative sample at 0 h) and 50 µM
Cu^{2+} ions had no effect on total motility but caused an
immediate switch from a non-agglutinated, motile and aggluti-
nated, non-motile and non-agglutinated, or non-motile and
agglutinated.

Copper caused significantly higher levels of sperm
agglutination than the other heavy metals tested
(Fig. 4). Copper-induced sperm agglutination was
immediate, specific and broad scale. In the presence
of copper, less than 1% of the sperm population
were motile and non-agglutinated at both 0 and 3 h
(Fig. 4). This effect was not evident in the other heavy
metals tested. Zinc and manganese had no effect
on sperm agglutination, and cobalt and iron only
showed a moderate decrease in the percentage of
non-agglutinated, motile spermatozoa at 3 h. None of
the heavy metals tested had an effect on total motility
at the dose tested (10 µM).

**Compared with other heavy metals, copper is a
significantly stronger agglutination agent**

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![Figure 2](image-url) A representative image of ram spermatozoa in
TALP + 250 µM PEN supplemented with (B) or without (A) 10 µM
Cu^{2+}. Video files of these two sperm populations can be viewed in
supplementary materials. Viewed under 400× magnification at 0 h of
incubation.

![Figure 3](image-url) Dose response (0–250 µM) of Cu^{2+} ions on ram sperm
agglutination in TALP supplemented with 250 µM PEN. Copper
caused mass agglutination of motile spermatozoa (open bars) at the
lowest dose tested (10 µM), which was accompanied by a reduction
in the percentage of non-agglutinated, motile spermatozoa
(black bars). Toxic effects are evident from 100 µM onwards with an
increase in the percentage of non-agglutinated, non-motile
spermatozoa (hatched bars) and an increase in non-motile,
agglutinated spermatozoa (grey bars) at the highest dose tested. Data
correspond to model derived mean ± s.e.m. for six replicate samples
assessed at 0 and 3 h and pooled over time. *P < 0.05 and
**P < 0.001 differences compared with control (0 µM).
Sialic acid has no effect on sperm agglutination

The supplementation of neutralised sialic acid to TALP had no effect on sperm motility or agglutination. The percentage of motile, non-agglutinated spermatozoa supplemented with 0 (3.2 ± 1.1%), 1 (3.0 ± 1.3%), 10 (3.5 ± 0.9%), 20 (3.8 ± 0.9%) or 30 (3.8 ± 1.0%) mM sialic acid was low and statistically similar. This suggests that the mechanism of sperm binding described herein does not involve a sialic acid-specific lectin as shown in goat spermatozoa (Roy et al. 2014).

Chelation of extracellular free cupric or cuprous ions is unlikely to be the sole mechanism by which PEN prevents sperm association

In comparison to the control (TALP only), both 1 mM EDTA and 1 mM BCS significantly increased the percentage of non-agglutinated, motile spermatozoa; however, this was only by a moderate amount compared with both 0.1 and 1 mM PEN (Fig. 5A). This indicates that chelation is unlikely to be the sole mechanism by which PEN prevents sperm association.

Protection from oxidative stress is unlikely to be the sole mechanism by which PEN prevents sperm association

Catalase (CAT) and α-tocopherol (VIT E) had no effect (Fig. 5B) on sperm agglutination compared with the control (TALP). l-ascorbic acid (VIT C; 3 h only) and superoxide dismutase (SOD; 0 and 3 h) significantly increased the percentage of non-agglutinated, motile spermatozoa compared with the control, but only by a moderate amount in comparison to 1 mM PEN (Fig. 5B). This indicates that protection from oxidative damage is unlikely to be the sole mechanism by which PEN prevents sperm association.

The reducing action of PEN is the most likely mechanism by which PEN prevents sperm association

The reductants showed the strongest anti-agglutination effect of all the compounds tested. Supplementation of
The influence of copper on sperm agglutination was shown to be highly specific as supplementation with a range of other heavy metals did not cause mass agglutination (Fig. 3). It is intriguing that ram spermatozoa are so susceptible to exogenous copper because they have higher sperm-bound copper levels (estimated to be 18.9 µM for humans) and higher seminal plasma copper levels than a range of species including the bull, boar, stallion and human (Mann 1964, Massanyi et al. 2003).

A copper-dependent lectin that causes sperm agglutination has been observed on the outer membrane of mature caprine spermatozoa (Roy et al. 2014). This lectin is sialic acid specific, and agglutinated cells could be dissociated with neutralised sialic acid. In this study, supplementation of neutralised sialic acid to TALP had no effect on sperm motility or agglutination, suggesting that the mechanism of sperm binding described herein does not involve a sialic acid-specific lectin as shown in goat spermatozoa.

We have previously shown that the thiol d-penicillamine (PEN) is highly effective in preventing or reversing sperm association in TALP (Leahy et al. 2016). PEN can act as a reducing agent, chelator or antioxidant;
however, it is unclear how PEN reduced agglutination. Cell aggregation has previously been linked to oxidative damage. Copper-induced lipid peroxidation has been implicated in platelet cell aggregation (Gorog & Kovacs 1995, Neiva et al. 1997) and protein aggregation in Alzheimer's and prion disease (Moir et al. 1999, Viles 2012). Copper catalyses the generation of reactive oxygen species (ROS), which attacks polysaturated fatty acids (PUFAs) of the sperm membrane and causes lipid peroxidation, sperm membrane destabilisation and cell death (Aitken et al. 1989). PEN can chelate transition metals that catalyse lipid peroxidation (Aitken et al. 2012a,b) or directly neutralise ROS (Gupte & Mumper 2007), limiting their ability to interfere with PUFAs of the sperm membrane. However, the range of antioxidants tested in this study showed no or minimal ability to prevent the agglutination of ram spermatozoa (Fig. 5B). l-ascorbic acid and superoxide dismutase (SOD) significantly increased the percentage of non-agglutinated, motile spermatozoa compared with the control but only by a moderate amount in comparison to PEN. Since l-ascorbic acid is a known reducing agent and SOD can chelate copper (Nordberg & Arnér 2001, Ottaviano et al. 2008), it is possible that these secondary functions, as a reductant or chelator, contributed to this response (Fig. 5B). The variable results obtained with the antioxidants tested indicate that protection from oxidative stress is unlikely to be the sole mechanism by which PEN prevents sperm association.

As excess free copper ions cause agglutination, and the well-known copper chelator PEN prevents agglutination, it would follow that chelation of copper is a likely mechanism by which PEN prevents sperm association. However, other chelators, such as EDTA and BCS, that have a high affinity for copper were not highly effective in preventing sperm agglutination (Fig 5A). EDTA is a membrane-permeable chelator that binds Cu2+ with a high copper stability constant (18.8) due to its six chelate rings (Ding et al. 2011). BCS is an impermeable chelator with a copper stability constant of 6.1, which selectively chelates Cu+ but will also bind Cu2+ (Patel et al. 1997). PEN has a similar copper stability constant (7.1) to BCS but is membrane permeable and can reduce Cu2+ to Cu+ and bind to either of these copper forms (Smith et al. 1994, Ding et al. 2011). Interestingly, despite displaying higher or similar affinity for copper as PEN, both BCS and EDTA showed minimal effects on sperm agglutination. Multiple studies have shown that PEN has lower affinity for copper in vitro than a range of other common chelators (e.g. EDTA and cysteine) but significantly higher copper affinity in vivo (Tran-Ho et al. 1997, Ding et al. 2011). For this reason, PEN remains the chelator of choice for the treatment of patients with copper accumulation due to Wilson's disease or other heavy metal intoxication (Walshe 2011). The superiority of PEN over EDTA in vivo implies that copper chelation therapy is unlikely to depend on complexation alone (Tran-Ho et al. 1997). The reasons why PEN is superior to EDTA for in vivo copper chelation therapy have been the focus of immense interest and are proposed to rely on two factors (1) that PEN can liberate Cu2+ from metalloproteins by reduction to Cu+ (May & Williams 1977) and (2) that PEN can form stable complexes with multiple ligands (Cu2+, Cu+ and other thiols) and produce a stable anionic multivalent copper cluster ([Cu62+Cu8+]3−PEN12Cl)5− (Birker & Freeman 1977, Kato et al. 1999). EDTA can prevent copper-dependent biological events when it is added to media containing free copper but cannot despoil copper from previously formed copper—protein complexes (Jimenez & Speisky 2000).

Of all the compounds tested, only the thiols (proteins with a sulphhydril bond), which act as reducing agents, showed strong anti-agglutination effects (Fig. 5C). This suggests that the mechanism of action of PEN is conferred by its ability to donate an electron to another molecule and act as a reductant in redox reactions (Fig. 7). Cysteine and DTT (1 mM) displayed similar levels of non-agglutinated spermatozoa at 0 h compared with 1 mM PEN but were less effective after 3 h. At the lower dose of 0.1 mM, PEN was also the most effective reducing agent. The analysis of the mechanisms underlying the oxidation of thiols explains why PEN may be more effective in initiating sperm disassociation and maintaining spermatozoa in a disassociated state. PEN has been proposed to undergo a higher rate of oxidation under physiological conditions (e.g. pH 7) compared with other thiols (e.g. cysteine 8.3 and glutathione 8.8) because the pKa of its SH-functional groups (7.9) is lower (Netter et al. 1987), making it more effective at lower doses. How PEN maintains the sperm population in a non-agglutinated form by keeping the copper complex in a reduced state is more complex. Smith et al. (1994) outlined the following reaction sequence for the oxidation of thiols by copper. Cupric ions react with RSH (where R denotes the R group of the thiol and SH denotes the sulphhydril bond of the thiol) to form a Cu2+—RSH complex in which Cu2+ is reduced to Cu+ and RSH is oxidised (RS•) (Reaction 1). Two of the radicals (RS•) react to form a disulphide (Reaction 2) and Cu+ reacts with a second thiol to form a Cu+ thiol complex (Reaction 3). The rate-limiting step of the process is considered (Smith et al. 1994) to rely on the reoxidation of the RSCu+ complex (Reaction 4), as it results in the release of Cu2+ where it can participate in further redox cycling (Reaction 1).
with other thiols, as the Cu⁺ is partially protected from re-binding at a slower rate, compared to other thiols on the sperm surface. Copper (Cu²⁺) causes the opposite effect by oxidising free sulphhydryl bonds to disulphide bonds.

Figure 7 Proposed model of ram sperm agglutination. The data presented in this article suggest a model by which PEN (denoted as PSH to show sulphhydryl bond) prevents or reverts sperm association by reducing the disulphide bonds (S–S) of a sperm protein to free sulphhydrils (SH). Copper (Cu²⁺) causes the opposite effect by oxidising free sulphhydryl bonds to disulphide bonds.

Reaction 1: 2Cu²⁺ + 2RSH → 2Cu⁺RS + 2H⁺
Reaction 2: 2RS → SSR
Reaction 3: 2Cu⁺ + RSH → 2CuSC
Reaction 4: 2CuSC + 2O₂ → 2Cu²⁺ + 2O₂

The rate of reoxidation of the RSCu⁺ complex is dependent on the R-group of the thiol (Smith et al. 1994). Reoxidation of Cu⁺ (Reaction 4) in a PEN complex is considered to occur at a slower rate, compared with other thiols, as the Cu⁺ is partially protected from further oxidative attack by sterically shielding from the two methyl groups (CH₃; Fig. 1) of the PEN side chain (Birker & Freeman 1977).

If sperm disassociation is occurring due to the reduction of copper bound to a sperm protein, or the reduction of a disulphide bond to free sulphhydrol groups in a sperm protein, then the re-association of spermatozoa is due to the re-oxidation of these proteins over time in the highly oxidising extracellular environment. Such a response is clearly evident when PEN is provided at a rate-limiting dose (0.1 mM) but not when excess PEN is present at the higher dose of 1 mM (Fig. 5). Reversible thiol—disulphide redox reactions are a functional switch for various important fertilisation-related signalling events. The oxidation of thiols to form disulphide bridges and the reduction of disulphide bridges to free sulphhydrols on the sperm surface have been shown to regulate capacitation-related sperm proteins (O’Flaherty 2015). PEN and other thiols have also been shown to initiate sperm release through the reduction of sperm surface disulphides to sulphhydrols (Talevi et al. 2007, Gualtieri et al. 2009).

A disintegrin and metalloproteinase (ADAM) proteins are good candidates for involvement in autologous sperm agglutination because they bind metals, are involved in cell adhesion (Seals & Courtneidge 2003, White 2003, Weber & Saftig 2012), contain a cysteine-rich domain and are abundant on the extracellular surface of the sperm membrane (Byrne et al. 2012). In this study, targeted inhibition of the ADAM metalloprotease domain significantly increased (Fig. 6) the percentage of motile, non-agglutinated spermatozoa (52.0% ± 7.8) compared with TALP (10.6% ± 6.1), suggesting that this domain may be involved in autologous sperm binding.

ADAMs are zinc-binding proteins; however, there are known examples that are activated by copper as metal binding sites of proteins are likely sites for oxygen-based reactions (Wilcox et al. 2001). For example, copper oxidises the zinc binding Cys residue of the HIV retrovirus nucleocapsid p7 protein (Yu et al. 1995). Oxidation of the Cys thiolate ligand does not affect binding of the zinc to the metalloprotease domain but results in three specific disulphide bonds among the six cysteines (Yu et al. 1995). Copper oxidation of one of the amino acid residues in the zinc binding site has also been shown to change the conformation of ADAM12-s to its mature, active form (Loechel & Wewer 2001). The ADAM metalloprotease domain participates in ectodomain shedding of multiple substrates including amyloid precursor protein, prion protein, heparin binding epidermal growth factor, tumour necrosis factor, t-selectin and various interleukins (Seals & Courtneidge 2003, White 2003, Weber & Saftig 2012). ADAMs cleave and remodel extracellular matrix proteins through the proteolytic release of these signalling factors (White 2003). Interestingly, many of these substrates have been shown to interact with copper (Hesse et al. 1994, Moir et al. 1999, Viles 2012, McDonald et al. 2014), and physiological concentrations of copper have been shown to stimulate zinc metalloproteinase ectodomain shedding of cell surface proteins. For example, copper-induced zinc metalloproteinase shedding of two key signalling and adhesion proteins, Jagged 1 and E-cadherin, was shown to be post-translationally modulated and enhanced the invasion of a PC3 cancer cell line (Par-Sturgess et al. 2012).

However, targeting of the integrin domain by pre-incubation with either 0.1 or 1 mM of the RGD blocking peptide had no effect on sperm agglutination (Fig. 6). Although this suggests that sperm agglutination is not dependent on RGD, it does not rule out ADAM-mediated cell adhesion. Only a subset of ADAM proteins, such as ADAM15, display the integrin binding motif Arg-Gly-Asp (RGD) in their disintegrin domain with the majority displaying an XCD (where X is an amino acid) sequence (Lu et al. 2010). Cell adhesion is also not restricted to the disintegrin domain of ADAM proteins. The cysteine-rich domain of ADAM proteins can bind directly to cell surface syndecans (ADAM12) (Iba et al. 2000) and the Von Willebrand factor (ADAM13) (de Groot et al. 2015). The mechanism by which ADAM proteins may mediate autologous sperm binding remains far from clear.
certain. Ongoing investigation on the influence of ADAM proteins in other fertilisation-related events, such as sperm–zona pellucida binding, will shed further light on the role of these multifunctional proteins in cell association and signalling within the reproductive tract (Dun et al. 2012, Okabe 2015).

Conclusion
In this study, we show that trace levels of copper ions cause mass agglutination of ram spermatozoa in a manner similar to that of TALP-induced sperm agglutination. The effect is highly specific as a similar response was not provoked by other heavy metals. The nucleophilic thiol, penicillamine, can act as an antioxidant, a reducing agent or a chelator and has previously been shown to prevent or reverse ram sperm agglutination. Comparison of PEN to compounds in these classes showed that only the reducing agents (particularly cysteine and DTT) displayed similar levels of non-agglutinated spermatozoa as PEN. This suggests that the mechanism of action of PEN is conferred by its ability to donate an electron to another molecule and act as a reducing agent in redox reactions. Together, these results indicate that PEN prevents sperm association by the reduction of disulphide bonds of a sperm membrane protein that binds copper. ADAM proteins are possible candidates, as targeted inhibition of the metalloproteinase domain of these proteins reduces agglutination; however, further research is required to elucidate how ADAM proteins mediate ram sperm agglutination.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Copper causes ram sperm agglutination


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