Abnormal folate metabolism causes age-, sex- and parent-of-origin-specific haematological defects in mice

Nisha Padmanabhan1,2, Katerina Menelaou1,2, Jiali Gao1, Alexander Anderson1,2, Georgina E. T. Blake1,2, Tanya Li1, B. Nuala Daw1,2 and Erica D. Watson1,2

1Department of Physiology, Development and Neuroscience, University of Cambridge, Cambridge, UK
2Centre for Trophoblast Research, University of Cambridge, Cambridge, UK

Edited by: Peying Fong & Bettina Mittendorfer

Key points

- Folate (folic acid) deficiency and mutations in folate-related genes in humans result in megaloblastic anaemia.
- Folate metabolism, which requires the enzyme methionine synthase reductase (MTRR), is necessary for DNA synthesis and the transmission of one-carbon methyl groups for cellular methylation.
- In this study, we show that the hypomorphic Mtrr<sup>gt/gt</sup> mutation in mice results in late-onset and sex-specific blood defects, including macrocytic anaemia, extramedullary haematopoiesis and lymphopenia.
- Notably, when either parent carries an Mtrr<sup>gt</sup> allele, blood phenotypes result in their genetically wildtype adult daughters, the effects of which are parent specific.
- Our data establish a new model for studying the mechanism of folate metabolism in macrocytic anaemia aetiology and suggest that assessing parental folate status might be important when diagnosing adult patients with unexplained anaemia.

Abstract

The importance of the vitamin folate (also known as folic acid) in erythrocyte formation, maturation and/or longevity is apparent since folate deficiency in humans causes megaloblastic anaemia. Megaloblastic anaemia is a type of macrocytic anaemia whereby erythrocytes are enlarged and fewer in number. Folate metabolism is required for thymidine synthesis and one-carbon metabolism, though its specific role in erythropoiesis is not well understood. Methionine synthase reductase (MTRR) is a key enzyme necessary for the progression of folate metabolism since knocking down the Mtrr gene in mice results in hyperhomocysteinaemia and global DNA hypomethylation. We demonstrate here that abnormal folate metabolism in mice caused by Mtrr<sup>gt/gt</sup> homozygosity leads to haematopoietic phenotypes that are sex and age dependent. Specifically, Mtrr<sup>gt/gt</sup> female mice displayed macrocytic anaemia, which might be due to defective erythroid differentiation at the exclusion of haemolysis. This was associated with...
Introduction

The importance of folate metabolism during erythropoiesis is demonstrated by the appearance of megaloblastic anaemia in folate-deficient humans. Megaloblastic anaemia is a type of macrocytic anaemia characterized by a low red blood cell (RBC) count, erythrocytes that are macrocytic, fewer immature RBCs (e.g. reticulocytes) and fewer platelets (Koury & Ponka, 2004). A critical characteristic of megaloblastic anaemia is the asynchronous maturation of the cytoplasmic and nuclear compartments of erythroid progenitors leading to abnormal morphology. Folate is essential for many biochemical reactions including de novo synthesis of purines and pyrimidines (Koury & Ponka, 2004). It also acts as a carrier of one-carbon methyl groups destined to methylate specific cellular targets. These include DNA (Jacob et al. 1998) and proteins, such as histones (Ghandour et al. 2002), the methylation of which is required to regulate chromatin structure and thus gene expression. Although the mechanism is unclear, the high rate of proliferation during erythropoiesis might make erythroid progenitors particularly susceptible to genomic instability (Menzies et al. 1966; Wickramasinghe et al. 1968; Yoshida et al. 1968; Koury et al. 1997). Additionally, epigenomic instability caused by global hypomethylation in the case of abnormal folate metabolism (Padmanabhan et al. 2013) might cause gene misexpression leading to abnormal differentiation or increased cell death of erythrocyte precursors.

Few animal models exist for the pathophysiological study of macrocytic anaemia related to folate deficiency. Mice fed a folate-free amino acid-based diet exhibit pancytopenia but lack macrocytic cells (Bills et al. 1992). However, when folate-deficient mice are infected with the Friend leukaemia virus, which increases the proliferation rate of erythrocyte precursors, megaloblastic erythroid cytosis is accentuated (Koury & Horne, 1994). Others have shown that when intestinal cells are unable to absorb folate, such as in Slec46a1−/− mice that lack the folate carrier PCFT, a severe case of macrocytic normochromic anaemia results (Salojin et al. 2011). Supplementation of folic acid, 5-methyltetrahydrofolate (5-methyl-THF) or folic acid promotes the survival of Slec46a1−/− mice by improving RBC parameters (Salojin et al. 2011). Similarly, mutations in the human SLC46A1 gene lead to folate malabsorption syndrome and megaloblastic anaemia (Erlacher et al. 2015). SLC19A1 (also known as reduced folate carrier 1, RFC1) is a protein essential for folate transport in mammalian cells. A knockout of the mouse Slc19a1 gene causes embryonic lethality (Gelineau-van Waes et al. 2008). However, when maternal folate supplementation was provided, Slc19a1−/− pups survived until birth, but died within 12 days postpartum due to a failure of haematopoietic organs (Zhao et al. 2001). Mutations in human genes associated with the metabolism of folate including methionine synthase (MTR) (Gulati et al. 1996; Leclerc et al. 1996) and methionine synthase reductase (MTRR) (Zavadakova et al. 2002; Vilaseca et al. 2003) also lead to megaloblastic anaemia. However, mice with mutations in the Mtr, Mtrr or Mthfr genes are not well characterized for haematological defects.

During the metabolism of folate, MTR is an enzyme responsible for exclusively transferring the methyl-group from 5-methyl-THF to homocysteine to form methionine and tetrahydrofolate (Shane & Stokstad, 1985). Methionine is a precursor to S-adenosyl methionine (S-AdoMet), which serves as a methyl-donor to cellular substrates including proteins, RNA and DNA (Wainfan & Maschio, 1975; Jacob et al. 1998; Ghandour et al. 2002), a process that requires methyltransferases. MTRR is a key enzyme necessary for the activation of MTR through the reductive methylation of its vitamin B12 cofactor (Yamada et al. 2006). Consequently, progression of the folate and methionine cycles requires MTRR enzymatic activity. A hypomorphic mutation of the mouse Mtrr gene (denoted as Mtrr<sub>hyp</sub>) disrupts folate metabolism by creating a ‘methyl trap’ as determined by an increase in plasma homocysteine and liver 5-methyl-THF concentrations, a reduction in plasma methionine and heart S-adenosyl methionine/S-adenosyl homocysteine ratio, and global increased renal Epo mRNA expression, hypercellular bone marrow, and splenic extramedullary haematopoiesis. In contrast, the male response differed since Mtrr<sup>+/−</sup> male mice were not anaemic but did display erythrocytic macrocytosis and lymphopenia. Regardless of sex, these phenotypes were late onset. Remarkably, we also show that when either parent carries an Mtrr<sup>−/−</sup> allele, a haematological defect results in their adult wildtype daughters. However, the specific phenotype was dependent upon the sex of the parent. For instance, wildtype daughters of Mtrr<sup>−/−</sup> females displayed normocytic anaemia. In contrast, wildtype daughters of Mtrr<sup>+/−</sup> males exhibited erythrocytic microcytosis not associated with anaemia. Therefore, abnormal folate metabolism affects adult haematopoiesis in an age-, sex- and parent-specific manner.

© 2018 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society
were generated by exploring whether an including megaloblastic anaemia. Therefore, we sought to examine the effects of abnormal folate metabolism on haematopoietic lineage. Here, we show that Mtrr<sup>®</sup> mice display haematological phenotypes, such as macrocytic anaemia, that are dependent upon sex and age.

It is well established that maternal or paternal folate deficiency in humans and mice increases the risk of developmental phenotypes in their offspring (MRC Vitamin Study Research Group, 1991; Lambrot et al. 2013), the most famous example of which is neural tube defects. However, little attention has been given to the parental effects of abnormal folate uptake or metabolism on adult-onset disease in their offspring, including megaloblastic anaemia. Therefore, we sought to explore whether an Mtrr<sup>®</sup> allele in female or male mice was sufficient to cause haematological abnormalities in their wildtype daughters (i.e. the F1 generation). Our study shows that wildtype F1 female mice display differential haematological defects, such as anaemia, depending on the Mtrr genotype of their mother or father. Altogether, we demonstrate that abnormal folate metabolism as caused by the Mtrr<sup>®</sup> allele affects haematopoiesis in an age-, sex- and parent-specific manner.

**Methods**

**Ethical approval**

This research was regulated under the Animals (Scientific Procedures) Act 1986 Amendment Regulations 2012 following ethical review by the University of Cambridge Animal Welfare and Ethical Review Body. The experiments were carried out according to the principles and regulations described by Grundy (2015).

**Mice and diet**

The Mtrr<sup>®</sup> mouse line was originally generated by a gene-trap (gt) insertion as previously described (Padmanabhan et al. 2013). Since the Mtrr<sup>®</sup> mutation was originally backcrossed into a C57D mouse genetic background (Padmanabhan et al. 2013), C57Bl/6 mice (The Jackson Laboratory, Bar Harbor, ME, USA) were used as controls in all experiments and were maintained in-house but separately from the Mtrr<sup>®</sup> mouse line. Mtrr<sup>®/gt</sup> mice were generated by Mtrr<sup>®/®</sup> intercrosses. The maternal or paternal effect of the Mtrr<sup>®</sup> allele was determined by analysis of Mtrr<sup>®/®</sup> females derived from either Mtrr<sup>®/gt</sup> females crossed to C57Bl/6 males or Mtrr<sup>®/®</sup> males crossed to C57Bl/6 females, respectively. All mice assessed were virgins. PCR genotyping was performed as previously described (Padmanabhan et al. 2013). Mice were fed a normal breeding diet (Rodent No. 3 breeding chow, Special Diet Services, Essex, UK) ad libitum from weaning onward. A full dietary breakdown of the chow was previously described (Padmanabhan et al. 2013). Mice were killed for tissue collection by cervical dislocation.

**Haematological profiling**

Two age groups of virgin mice were analysed: female and male mice at 7 weeks of age, and female and male mice averaging 5 months of age (n = 3–5 mice per sex per age group). The parental effect of the Mtrr<sup>®</sup> mutation was determined in 5-month-old wildtype F1 female mice (n = 6–7 mice per pedigree). Age- and sex-matched C57Bl/6 mice were used as controls (n = 5–6 mice per experiment). Peripheral blood was collected with a 25-gauge needle through direct cardiac puncture after cervical dislocation. Fresh blood samples were placed into ethylene diamine tetraacetic acid (EDTA)-coated tubes and sent for machine blood count analysis at Central Diagnostic Services, Clinical Pathology Laboratory, Cambridge Veterinary School, University of Cambridge. The profiles for C57Bl/6 mice were comparable to standard values (Russell & Meier, 1968). Blood smears were prepared and analysed to confirm the findings. The reticulocyte production index (RPI) was calculated as previously described (Salojin et al. 2011). Briefly, the percentage of reticulocytes in peripheral blood was multiplied by the ratio of peripheral blood haematocrit (HCT) to the mean HCT in the C57Bl/6 group (%Reticulocytes × [HCT/(mean C57Bl/6 HCT)]). The RPI was further adjusted for longer lifespan of reticulocytes in mice with low HCT by dividing RPI values by the reticulocyte maturation index (Prouty, 1979), which was arbitrarily set to 1 for blood samples with HCT greater than 41.0%, and to 1.5 for samples with HCT values within the 31.0–40.9% range (Salojin et al. 2011).

**Bone marrow isolation**

Bone marrow cells were isolated from female femurs (n = 3–4 mice per pedigree) based on a published protocol (Swamydas & Lionakis, 2013). Briefly, muscles were removed from femur and humerus bones, which were then washed in 1x phosphate buffered saline (PBS). The epiphyses of the bones were removed with a scalpel and, using a 25-gauge needle, the bone marrow cells were flushed out with 1x PBS. The inner surface of the bones was scraped with the needle to ensure efficient removal of cells. The cell suspension was centrifuged at 300 × g for 7 min at 4°C and the resulting pellet was frozen in liquid nitrogen and stored at −80°C.

**Histology**

Tissue was dissected from 3–6 mice per sex and per genotype/pedigree. Femurs with muscle removed were fixed in 10% neutral buffered formalin for 48 h at 4°C and washed in 1x PBS. The bones were treated with...
Decalciﬁng Solution-Lite (Sigma-Aldrich, Gillingham, UK) before preparing for parafﬁn embedding. Spleens were ﬁxed in 4% paraformaldehyde in 1x PBS and prepared for parafﬁn embedding using standard techniques. Parafﬁn blocks were sectioned to 7 μm. Tissues were stained with haematoxylin and eosin (H & E) using standard procedures.

Immunohistochemistry and Prussian blue stain

Parafﬁn-embedded tissue sections were de-waxed, rehydrated and washed in 1x PBS. For immunohistochemistry staining, tissue sections were incubated in 3% H2O2 in 1x PBS for 30 min, treated with trypsin tablets (Sigma-Aldrich) for 10 min, and then incubated with blocking serum (5% donkey serum, 1% bovine serum albumin in 1x PBS) for 1 h. Tissue was incubated in rabbit anti-mouse Ki67 (Abcam, Cambridge, UK, cat. no. ab15580, RRID:AB_443209) diluted to 1:100 in blocking serum overnight at 4°C, and then in donkey anti-rabbit IgG conjugated to horseradish peroxidase (Abcam cat. no. ab6802, RRID:AB_955445) diluted to 1:300 in blocking serum for 1 h at room temperature. Peroxidase substrate reactions were conducted with DAB (3,3′-diaminobenzidine) chromagen substrate kit (Abcam cat. no. ab64238) according to the manufacturer’s instructions. For Prussian blue stain, tissue was placed in a 50:50 working solution of 0.01 M potassium ferrocyanide and 0.6% hydrochloric acid for 15 min. Sections were counterstained with Nuclear Fast Red (Sigma-Aldrich) before dehydration, clearing and mounting in DPX medium (Sigma-Aldrich).

RNA extraction and quantitative reverse transcription PCR (RT-qPCR)

Tissue was homogenized using Lysing Matrix D beads (MP Biomedicals, Carlsbad, CA, USA). Total RNA extraction was completed using Trizol (Sigma-Aldrich), the GenElute Mammalian Total RNA Miniprep Kit (Sigma-Aldrich), or AllPrep DNA/RNA Mini Kit (QIAGEN, Manchester, UK) according to the manufacturer’s instructions. All extracts were treated with DNase I (Thermo Scientific, Waltham, MA, USA). Reverse-transcription reactions were performed with the RevertAid H Minus First Strand complementary DNA (cDNA) Synthesis Kit (Thermo Scientiﬁc) by using 2–5 μg of RNA in a 20 μL reaction according to the manufacturer’s instructions. PCR ampliﬁcation of Runx1b, Hbb, Ftl1 and Hamp1 transcripts was conducted using MESA SYBR Green qPCR MasterMix Plus (Eurogentec, Liege, Belgium). PCR ampliﬁcation of Epo transcripts was conducted using FastStart TaqMan Probe master mix (Roche, Basel, Switzerland). A DNA Engine Opticon 2 thermocycler (BioRad, Hercules, CA, USA) was used in both cases. Transcript levels were normalized to Gapdh, Actb and/or Hprt RNA levels, and the fold change was quantiﬁed using the standard curve method (Runx1b, Hbb and Hamp1) or the comparative Ct method (Epo). cDNA levels in C57Bl/6 tissue were normalized to 1. Experiments were conducted in duplicate or triplicate with at least three biological replicates. Primer sequences were as follows: Actb (forward [F]) 5′-CCC TAA GGA CAA CCG TGA A, (reverse [R]) 5′-CAG CCT GGA TGG CTA CTG ACA; Epo (F) 5′-TCT GCG ACA GTC GAG TCC TG, (R) 5′-CTG CAC AAC CCA TCG T; Ftl1 (F) 5′-CCT CGC TGC TGG CTT CAG CTC, (R) 5′- AAA GAA GCC CAG AGA GAG GT; Gapdh (F) 5′-CAT GCC CTT CCG TGT TCC T, (R) 5′-GGC GCA CTG CAG ATC CA (Gilllich et al. 2012); Hamp1 (F) 5′-GAT GGC ACT CAG CAC TCG, (R) 5′-GCT GCA GCT CTG TAG TCT GTC T (Patel et al. 2012); Hbb (F) 5′- GTC TCT GGC CTG TGG GGA AA, (R) 5′-CCA CCA GCA GCC TGC CC; Hprt (F) 5′-TCC TCC TCC TAC GCG TT T T, (R) 5′- CCT GGT TCA TCA TGC ATC ATC; Runx1b (F) 5′-CCT CCG GTA GTA AAG GAG TCT G, (R) 5′-CCG ATT GAG TAA GGA CCC TGA A (Challen & Goodell, 2010).

Total homocysteine concentrations

Total homocysteine concentrations in plasma were simultaneously measured by the Biochemical Genetics Unit, Department of Clinical Biochemistry, Cambridge University Hospitals NHS Foundation Trust using underivatized liquid chromatography tandem-mass spectrometry (LC-MS/MS) (Waters ACQUITY liquid chromatography system and Quattro Premier mass spectrometer) operated in electrospray ionization positive mode as was previously described in detail (Padmanabhan et al. 2013).

Equipment and software

A Zeiss AXIO Imager A.1 light microscope with a Zeiss AxioCam MRc5 camera and AxioVision 4.7.2 imaging software program (Zeiss, Oberkochen, Germany) were used to obtain cell and tissue images. Cell counts, Prussian blue staining intensity and other histological measurements were performed using ImageJ (64-bit) software (NIH, Bethesda, MD, USA). Graphs were generated using GraphPad Prism 6 software (GraphPad Software Inc., La Jolla, CA, USA).

Statistical analysis

Statistical analyses were performed using GraphPad Prism 6 software. Data were analysed using independent Student’s t tests or ordinary one-way ANOVA with Tukey multiple comparison tests. P values less than 0.05 were considered significant.
Results

Mtrr<sup>−/−</sup> female mice display macrocytic anaemia

To determine whether abnormal folate metabolism leads to haematological anomalies in mice, peripheral blood was collected from 5-month-old Mtrr<sup>−/−</sup> mice for profiling and compared to similar age C57Bl/6 controls. Both female and male Mtrr<sup>−/−</sup> mice displayed red blood cell (RBC) distribution widths that were significantly greater than controls (P < 0.03) indicating more variable RBC size in the Mtrr<sup>−/−</sup> mice (Fig. 1A and B). The mean corpuscular volumes were also significantly higher than controls (P < 0.026; Fig. 1A) indicating macrocytosis. Despite this, a higher frequency of microcytic cells was also detected in peripheral blood smears but only in Mtrr<sup>−/−</sup> males compared to C57Bl/6 males (Fig. 1B and C). Consistent with the broader appearance of macrocytic cells, the mean corpuscular haemoglobin (MCH) level was also significantly higher in female and male Mtrr<sup>−/−</sup> mice (P < 0.03) and the mean corpuscular haemoglobin concentration (MCHC) was unchanged (P > 0.19; Fig. 1A). Importantly, Mtrr<sup>−/−</sup> females (P = 0.043) but not Mtrr<sup>−/−</sup> males (P = 0.302) exhibited significantly lower RBC counts compared to C57Bl/6 suggesting sex-specific anaemia (Fig. 1A). Although haemoglobin levels showed a downward trend in female Mtrr<sup>−/−</sup> mice compared to C57Bl/6 females (P = 0.085), haemoglobin and haematocrit levels were not significantly different in all Mtrr<sup>−/−</sup> mice assessed (Fig. 1A). Together, these data indicate that Mtrr<sup>−/−</sup> mice display RBC macrocytosis and, notably, this finding was associated with anaemia only in Mtrr<sup>−/−</sup> females.

Remarkably, significantly more reticulocytes (RBC precursor cells) were observed in the peripheral blood of Mtrr<sup>−/−</sup> female mice (P = 0.009) and not Mtrr<sup>−/−</sup> males (P = 0.131) compared to C57Bl/6 mice (Fig. 1A). This observation was supported by a higher reticulocyte production index (P = 0.003; Fig. 1A) and an increased frequency of polychromatophilic cells in the peripheral blood smears only in Mtrr<sup>−/−</sup> females (P < 0.05; Fig. 1B and D). These data suggest that abnormal folate metabolism in Mtrr<sup>−/−</sup> females might promote increased formation of erythroid progenitor cells to compensate for the anaemic state or, alternatively, abnormal differentiation of reticulocytes may occur.

Increased frequency of Howell–Jolly bodies in Mtrr<sup>−/−</sup> RBCs

Howell–Jolly bodies are erythrocyte micronuclei that fail to be expelled during maturation. Even though Howell–Jolly bodies are present in normal circulating mouse RBCs (Bannerman, 1983), a significantly higher percentage of RBCs containing Howell–Jolly bodies (nuclear fragments) were observed in both Mtrr<sup>−/−</sup> females and males compared to control C57Bl/6 mice (Fig. 1B and E). These bodies are frequently associated with megaloblastic anaemia and folate deficiency in humans (Koury & Ponka, 2004), and may be indicative of altered splenic function (Corazza et al. 1990) or impaired erythrocytic maturation.

Mtrr<sup>−/−</sup> mice show sex-specific abnormalities in lymphocyte counts

To explore whether the effects of abnormal folate metabolism were specific to the erythroid lineage, other blood cell populations in peripheral blood were assessed (Fig. 1F–I). Myeloid lineages, such as platelets, neutrophils, monocytes, eosinophils and basophils were present in normal numbers in Mtrr<sup>−/−</sup> male and female mice (Fig. 1F–I). Despite this, Mtrr<sup>−/−</sup> males displayed a significant decrease in lymphocytes compared to control C57Bl/6 males (P = 0.005) resulting in an overall decrease in white blood cell (WBC) counts (P = 0.013; Fig. 1H and I). In contrast, Mtrr<sup>−/−</sup> females displayed lymphocytes and WBC numbers that were within the normal range (P > 0.16; Fig. 1H and I). Altogether, these data indicate that the differentiation potential of multiple haematopoietic lineages is influenced by Mtrr deficiency in a sex-specific manner.

The haematological effects of Mtrr deficiency emerge with age

To determine whether the haematological effects of Mtrr deficiency were age related, the peripheral blood of C57Bl/6 and Mtrr<sup>−/−</sup> mice at 7 weeks of age was characterized. Blood profiles of young Mtrr<sup>−/−</sup> female and male mice were largely within the normal range compared to controls (Fig. 2). However, young male and female Mtrr<sup>−/−</sup> mice displayed significantly more microcytic RBCs than controls (P < 0.0001; Fig. 2B and C), though the mean corpuscular volume and RBC distribution widths were unchanged (Fig. 2A). Furthermore, significantly more microcytes were present in young Mtrr<sup>−/−</sup> mice than older Mtrr<sup>−/−</sup> mice (P = 0.008; Figs 1C and 2C). This difference was not present in young versus old C57Bl/6 mice (P > 0.50; Figs 1C and 2C). More Howell–Jolly bodies were also found in RBCs as early as 7 weeks in male and female Mtrr<sup>−/−</sup> mice compared to controls (Fig. 2B and E). Altogether, these data suggest that the peripheral blood phenotype observed in Mtrr<sup>−/−</sup> mice largely emerges with age. However, the increased presence of Howell–Jolly bodies and microcytes precedes the appearance of the other blood phenotypes in mice with abnormal folate metabolism.
Figure 1. Sexually dimorphic haematological defects in peripheral blood from Mtrrgt/gt mice compared to C57Bl/6 controls at 5 months of age

Haematological profiles of peripheral blood from C57Bl/6 control mice (black symbols) versus Mtrrgt/gt mice (grey symbols) at 5 months of age. Graphical data are presented as means ± SD. Blood from female (f, circles) and male (m, squares) mice was assessed. n = 3–10 mice per sex and genotype. A, graphs indicating erythroid cell characteristics of C57Bl/6 and Mtrrgt/gt mice. MCV, mean corpuscular volume; RDW, red blood cell distribution width; RBC, red blood cells; Hct, haematocrit; Hb, haemoglobin; MCH, mean corpuscular haemoglobin; MCHC, mean corpuscular haemoglobin concentration; RPI, reticulocyte production index. B, representative images of peripheral blood smears from C57Bl/6 and Mtrrgt/gt mice. Blood from female (f) and male (m) mice was assessed. Black arrowheads indicate RBCs with Howell–Jolly bodies. White arrowhead indicates a microcytic cell. Scale bars: 10 μm; insets, 3 μm. C–E, graphs indicating the percentage of RBCs that were microcytic (C), polychromatic (D) or contained Howell–Jolly bodies (HJBs, E) in peripheral blood smears of C57Bl/6 and Mtrrgt/gt mice. Blood from female (f) and male (m) mice was assessed. Black arrowheads indicate RBCs with Howell–Jolly bodies. C⃝ 2018 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society
Figure 2. *Mtrrgt* mice at 7 weeks have normal peripheral blood haematological profiles

Haematological profiles of peripheral blood from C57Bl/6 control mice (black symbols) versus *Mtrrgt* mice (grey symbols) at 7 weeks of age. Graphical data are presented as means ± SD. Blood from female (f, circles) and male (m, squares) mice was assessed. *n* = 3–5 mice per group. A, graphs indicating erythroid cell characteristics of C57Bl/6 and *Mtrrgt* mice. MCV, mean corpuscular volume; RDW, red blood cell distribution width; RBC, red blood cells; Hct, haematocrit; Hb, haemoglobin; MCH, mean corpuscular haemoglobin; MCHC, mean corpuscular haemoglobin concentration; RPI, reticulocyte production index. B, representative peripheral blood smears from C57Bl/6 and *Mtrrgt* mice. Blood from female (f) and male (m) mice was assessed. Black arrowheads indicate RBCs with Howell–Jolly bodies. White arrowhead indicates a microcytic cell. Scale bars: 10 μm. C–E, graphs indicating the percentage of RBCs that were microcytic (C), polychromatic (D) or contained Howell–Jolly bodies (HJBs, E) in peripheral blood smears of C57Bl/6 and *Mtrrgt* mice. Blood from female (f) and male (m) mice was assessed. Black arrowheads indicate RBCs with Howell–Jolly bodies. White arrowhead indicates a microcytic cell. Scale bars: 10 μm. F–L, graphs indicating the number of platelets (F), neutrophils (G), white blood cells (WBC, H), lymphocytes (I), basophils (J), eosinophils (K) and monocytes (L) in peripheral blood of C57Bl/6 and *Mtrrgt* mice. Statistical analysis: unpaired *t* tests were performed to independently compare C57Bl/6 females to *Mtrrgt* females or C57Bl/6 males to *Mtrrgt* males. *P* < 0.05, **P** < 0.01, ***P*** < 0.001. [Colour figure can be viewed at wileyonlinelibrary.com]
Erythropoietin (EPO) is a key hormone regulator of erythropoiesis. It is synthesized by the kidney to promote the formation of RBCs by acting on erythroid precursor cells in the bone marrow. Increased EPO levels are associated with anaemia (Koury & Ponka, 2004). As expected, Mtrrgt/gt male kidneys displayed normal levels of Epo mRNA expression (Fig. 3A) compared to controls regardless of age. In contrast, a 3.0-fold and 8.3-fold increase in Epo mRNA levels were apparent in young and old Mtrrgt/gt female kidneys, respectively, compared to C57Bl/6 females (P < 0.001; Fig. 3A). While anaemia was absent in young Mtrrgt/gt female mice (Fig. 2A), increased Epo expression suggests that there may be an early, less severe anaemia phenotype that becomes progressively worse with age.

To further assess the effects of abnormal folate metabolism on haematopoiesis, histological sections of bone marrow of older females were analysed. Mtrrgt/gt females displayed hypercellular bone marrow compared to C57Bl/6 controls (Fig. 3B and C). Additionally, the total area of bone marrow represented by adipocytes was substantially reduced in Mtrrgt/gt females (0.7% versus 11.1% in C57Bl/6 females; P = 0.0003) (Fig. 3B and D). This observation may be important because marrow adipocytes are known to suppress the haematopoietic niche (Rosen et al. 2009). Furthermore, normal progression of erythroid differentiation depends upon reduced expression of Runx1 (North et al. 2002), a gene that encodes a transcription factor normally expressed in haematopoietic stem cells in the bone marrow and colony forming units in the spleen (North et al. 2002; Maki et al. 2005). Hypercellular bone marrow and anaemia in mice are associated with decreased Runx1 mRNA expression (Zhou et al. 2015). Indeed, Runx1b mRNA expression was significantly decreased in Mtrrgt/gt female bone marrow and spleens compared to controls (Fig. 3E) as determined by quantitative reverse transcription PCR (RT-qPCR) analysis. A downregulation of Hbb mRNA expression in bone marrow of Mtrrgt/gt females was also observed (Fig. 3F). Under normal circumstances, the haemoglobin β chain complex (HBB) encourages erythrocyte maturation (Dore & Crispino, 2011). Altogether, these data support the hypothesis that the bone marrow of Mtrrgt/gt female mice displays an increased erythroid precursor population that may be unable to fully mature into erythrocytes causing anaemia.

Instead of an erythroid differentiation defect in Mtrrgt/gt females, an alternative hypothesis proposes that RBC haemolysis is the cause of anaemia as was observed in folate-deficient mice and Slc46a1 knockouts (Bills et al. 1992; Salojin et al. 2011). Histological sections of C57Bl/6 and Mtrrgt/gt female and male spleens were exposed

Figure 3. Abnormal erythroid differentiation, not haemolysis, is likely the cause of anaemia in Mtrrgt/gt female mice

Graphical data show values from C57Bl/6 (black symbols) and Mtrrgt/gt (grey symbols) mice and are presented as means ± SD. A, RT-qPCR analysis of erythropoietin (Epo) mRNA expression in kidneys from 7-week-old (young) and 5-month-old (older) C57Bl/6 and Mtrrgt/gt mice. mRNA expression levels of female (f, circles) and male (m, squares) mice are indicated. n = 3–5 mice were analysed per group. Data are presented as fold change compared to same sex C57Bl/6 controls (normalized to 1). B, representative images of H & E stained histological sections of bone marrow of older C57Bl/6 and Mtrrgt/gt female mice. White arrowheads indicate adipocytes. Scale bars: 10 μm. C and D, graphs indicating the number of bone marrow (BM) cells per designated area (a.u., arbitrary units, C) and percentage of total bone marrow area represented by adipocytes (Ad) in older C57Bl/6 and Mtrrgt/gt female mice (D). E and F, graphs showing an RT-qPCR analysis of Runx1b mRNA in bone marrow (BM) and spleen (Sp) (E) and Hbb mRNA expression in bone marrow (F) of C57Bl/6 and Mtrrgt/gt older female mice. n = 3–4 mice were analysed per group. Data are presented as fold change compared to C57Bl/6 controls (normalized to 1). Statistical analysis: unpaired t tests were performed to independently compare C57Bl/6 females to Mtrrgt/gt females or C57Bl/6 males to Mtrrgt/gt males. *P < 0.05, **P < 0.01, ***P < 0.001. [Colour figure can be viewed at wileyonlinelibrary.com]
to Prussian blue stain to determine the degree of iron deposition as an indicator of haemolysis. No significant difference in iron deposition was observed in Mtrrgt/gt spleens compared to controls (Fig. 4A and B). Next, using RT-qPCR, we measured ferritin light chain 1 (Ftl1) mRNA expression since FTL1 mediates iron uptake and its expression is iron dependent (Arosio et al. 2015). Ftl1 mRNA expression in bone marrow and spleens was within the normal range in Mtrrgt/gt compared to C57Bl/6 control females (P > 0.08; Fig. 4C). Furthermore, we assessed hepatic Hamp1 expression, a gene that encodes hepcidin, a hormone regulator of iron storage. Increased hepcidin production normally occurs when iron is abundant and is suppressed during erythropoiesis to make iron available for haemoglobin synthesis (Ganz & Nemeth, 2012). In Mtrrgt/gt females and males, Hamp1 mRNA expression was similar to C57Bl/6 controls (Fig. 4D). Together, these data suggest that anaemia caused by Mtrr deficiency in female mice is unlikely to be due to haemolysis of RBCs.

**Splenomegaly and extramedullary erythropoiesis observed in female Mtrr<sup>gt/gt</sup> mice**

Splenomegaly and extramedullary haematopoiesis are often associated with anaemia in humans. Older Mtrrgt/gt female mice, which were anaemic (Fig. 1A), displayed splenomegaly since the average splenic weight was significantly higher than C57Bl/6 female spleens (P < 0.05; Fig. 5A). A similar effect was absent in Mtrrgt/gt males (Fig. 5A), which did not display anaemia in peripheral blood (Fig. 1A). Further analysis of splenic regions revealed that the white pulp, red pulp and marginal zone displayed a similar regional area (Fig. 5B) and organization (Fig. 5D–G) in Mtrrgt/gt female and male spleens compared to C57Bl/6 controls. However, a high degree of fibrosis was apparent in female Mtrrgt/gt spleens (Fig. 5D and E), which may indicate degenerative lesions and disease (Cesta, 2006). Cell counts in histological sections revealed an increased density of cells in the white pulp of Mtrrgt/gt female and male spleens (Fig. 5C, H–K), though there was no change in occurrence of mitotic cells in this region as indicated by Ki67 immunostaining (Fig. 5P–S and X). Although difficult to quantify, histological sections of red pulp in Mtrrgt/gt female spleens were qualitatively more densely packed with mature erythrocytes (Fig. 5L and M). Clusters of cells, possibly erythroid progenitors, were apparent in the red pulp of Mtrrgt/gt female spleens (Fig. 5M), though not in Mtrrgt/gt male spleens (Fig. 5O) or controls (Fig. 5L and N). This observation may indicate the presence of extramedullary erythropoiesis, which is consistent with anaemia detected in peripheral blood (Cesta, 2006). Furthermore, this extramedullary haematopoiesis was associated with a decrease in Runx1b expression, a gene that encodes hepcidin, in older C57Bl/6 (black) and Mtrrgt/gt (grey) livers. Female (f, circles) and male (m, squares) as determined by ImageJ software. C, RT-qPCR analysis of Ftl1 mRNA expression in bone marrow (BM) and spleens (Sp) of older C57Bl/6 (black symbols) and Mtrrgt/gt (grey symbols) females (f, circles) and males (m, squares) as determined by ImageJ software. D, RT-qPCR analysis of Hamp1 mRNA expression (gene that encodes hepcidin) in older C57Bl/6 (black) and Mtrrgt/gt (grey) female mice. D, RT-qPCR analysis of Hamp1 mRNA expression (gene that encodes hepcidin) in older C57Bl/6 (black) and Mtrrgt/gt (grey) livers. Female (f, circles) and male (m, squares) livers were assessed. For RT-qPCR data: n = 3–8 mice were analysed per group and data are presented as fold change compared to C57Bl/6 controls (normalized to 1; mean ± SD). Statistical analysis: unpaired t tests were performed to independently compare C57Bl/6 females to Mtrrgt/gt females or C57Bl/6 males to Mtrrgt/gt males. [Colour figure can be viewed at wileyonlinelibrary.com]
mRNA expression in MtrρρΔgt female spleens (P = 0.05; Fig. 3E) and an overall increase in Ki67-expressing cells in the red pulp of MtrρρΔgt spleens including in regions of presumed extramedullary haematopoiesis in MtrρρΔgt females (Fig. 5T–X). Overall, these data suggest that abnormal folate metabolism results in female-specific macrocytic anaemia associated with splenomegaly and extramedullary erythropoiesis.
Presence of a parental Mtrr<sup>gt</sup> allele leads to abnormal haematological profiles in their wildtype daughters

We previously showed that when mice are carriers of an Mtrr<sup>gt</sup> allele, it is sufficient to cause abnormal phenotypes several wildtype generations later (Padmanabhan et al. 2013). This multigenerational effect occurs only through the maternal lineage (i.e. the maternal grandmother or maternal grandfather) (Padmanabhan et al. 2013). Therefore, to explore whether there is a generational effect of abnormal folate metabolism on haematopoiesis, we completed a similar analysis as above in wildtype F1 females of an Mtrr<sup>+</sup>/gt parent. To do this, Mtrr<sup>+</sup>/gt male mice were mated with C57Bl/6 females and Mtrr<sup>+</sup>/gt female mice were mated with C57Bl/6 males to assess a paternal and maternal effect, respectively. All analyses were completed in non-pregnant F1 females and C57Bl/6 female mice were used as controls. First, using tandem mass spectrometry, we determined that the wildtype F1 females from each pedigree showed total plasma homocysteine concentrations that were within the normal range of C57Bl/6 female mice (Fig. 6). This result indicates that one-carbon metabolism in wildtype F1 females remains unaffected by parental Mtrr<sup>gt</sup> heterozygosity.

Next, peripheral blood was collected from 4- to 5-month-old wildtype daughters (n = 6–7 mice) from each pedigree and compared to blood from similar aged C57Bl/6 control females (n = 6 mice). Comparable to Mtrr<sup>gt/gt</sup> female mice, the peripheral blood of wildtype F1 females derived from Mtrr<sup>+</sup>/gt mothers exhibited reduced RBC counts and haemocrit compared to controls (Fig. 7A) indicating anaemia. However, these cells were not macrocytic as determined by mean corpuscular volume (Fig. 7A). On the other hand, wildtype F1 females derived from Mtrr<sup>+</sup>/gt fathers did not display anaemia since their peripheral RBC counts were within the normal range (Fig. 7A). Also in contrast to the effects of Mtrr<sup>gt</sup> homozygosity in females and of maternal Mtrr<sup>gt</sup> heterozygosity, the RBCs of these wildtype F1 females showed a decreasing trend in mean corpuscular volume compared to C57Bl/6 controls (P = 0.060, Fig. 7A) and were less variable in size compared to C57Bl/6 controls as demonstrated by a lower RBC distribution width (P = 0.04; Fig. 7A and B). In support of this finding, significantly more microcytic RBCs were present in the blood smears of F1 females derived from Mtrr<sup>+</sup>/gt fathers compared to controls (Fig. 7B and C), an observation comparable to Mtrr<sup>gt/gt</sup> males (Fig. 1C).
Figure 7. Mtrr<sup>gt</sup> heterozygosity causes haematological defects in peripheral blood profiles of their adult wildtype daughters in a parent-specific manner

Haematological profiles of peripheral blood from C57Bl/6 control female mice (white) versus wildtype (Mtrr<sup>+/+</sup>) F1 female mice derived from either an Mtrr<sup>gt</sup>/<sup>gt</sup> mother (Mat; light grey) or an Mtrr<sup>gt</sup>/<sup>gs</sup> father (Pat; dark grey). Graphical data are presented as means ± SD. n = 6–7 mice were analysed per group. A, graphs indicating erythroid cell characteristics of C57Bl/6 females and wildtype F1 females derived from either an Mtrr<sup>gt</sup>/<sup>gt</sup> mother or father. MCV, mean corpuscular volume; RDW, red blood cell distribution width; RBC, red blood cells; Hct, haematocrit; Hb, haemoglobin; MCH, mean corpuscular haemoglobin; MCHC, mean corpuscular haemoglobin concentration; RPI, reticulocyte production index. B, representative images of peripheral blood smears from C57Bl/6 females and wildtype F1 females derived from an Mtrr<sup>gt</sup>/<sup>gs</sup> mother (Mat) or father (Pat). Inset: black arrow indicates a codocyte. White arrowhead indicates a microcytic cell. Scale bars: 10 μm; inset, 2.5 μm. C–E, graphs indicating the percentage of RBCs that were microcytic (C), polychromatic (D) or contained Howell–Jolly bodies (HJBs, E) in peripheral blood smears of C57Bl/6 females and wildtype F1 females derived from an Mtrr<sup>gt</sup>/<sup>gs</sup> mother or father. F–L, graphs indicating the number of platelets (F), neutrophils (G), white blood cells (WBC, H), lymphocytes (I), basophils (J), eosinophils (K) and monocytes (L) in the peripheral blood of C57Bl/6 females and wildtype F1 females derived from an Mtrr<sup>gt</sup>/<sup>gs</sup> mother or father. Statistical analysis: ordinary one-way ANOVA with Tukey multiple comparison tests was performed. *P = 0.060, †P < 0.05, ‡P < 0.005, §P < 0.001. Pedigree legend: circle, female; square, male; grey outline, C57Bl/6 mice; black outline, Mtrr mouse line; white fill, Mtrr<sup>+/+</sup>; half white/half black fill, Mtrr<sup>gt</sup>gt. [Colour figure can be viewed at wileyonlinelibrary.com]
Blood defects caused by intrinsic and parental Mtrr mutation

Figure 8. Wildtype F1 females derived from an Mtrr<sup>+/gt</sup> parent display hypercellular bone marrow and no splenic defects

Graphical data show values from C57Bl/6 (white) and wildtype F1 females derived from an Mtrr<sup>+/gt</sup> mother (Mat; light grey) or Mtrr<sup>+/gt</sup> father (Pat; dark grey) mice. Values are presented as means ± SD. n = 3–5 mice per group were assessed. A, RT-qPCR analysis of erythropoietin (Epo) mRNA expression in kidneys (Ki). Data are presented as fold difference compared to C57Bl/6 controls (normalized to 1). B, graphs indicating the number of bone marrow (BM) cells per designated area (a.u., arbitrary units; left-hand graph) and the percentage of total bone marrow area represented by adipocytes (Ad; right-hand graph). C, histological sections of bone marrow from C57Bl/6 and wildtype F1 females derived from Mtrr<sup>+/gt</sup> mothers (Mat) or Mtrr<sup>+/gt</sup> fathers (Pat). Scale bars: 10 μm. D, the average splenic (Sp) weight for each group is assessed. E, data indicating the percentage of splenic area divided into major components including white pulp (WP, green bar), red pulp (RP, pink bar) and marginal zone (MZ, blue bar) for each female group. F–H, H & E-stained histological sections of spleens from C57Bl/6 females (left panel), and wildtype F1 females derived from an Mtrr<sup>+/gt</sup> mother (Mat; centre panel) or an Mtrr<sup>+/gt</sup> father (Pat; right panel). White boxes in F indicate regions of higher magnification shown in panels directly below and show the white pulp (WP, G) or red pulp (RP, H) from each pedigree. Scale bars: F, 200 μm; G–H, 10 μm. I–J, graphs showing the number of splenic white pulp (WP) cells in a defined area (mm<sup>2</sup>, I) and the percentage of Ki67-positive cells in the white pulp (WP) and red pulp (RP, J) of spleens from each female group. K, the relative intensity of Prussian blue (PB) stain in spleens to indicate iron deposition in each female group as determined...
Even though maternal $\text{Mtrr}^{gt}$ heterozygosity caused anaemia in their wildtype daughters and paternal $\text{Mtrr}^{gt}$ heterozygosity did not, reticulocyte counts and reticulocyte production indices were comparable to controls in both cases (Fig. 7A and D). Despite this observation, renal $\text{Epo}$ mRNA expression was increased in wildtype F1 females from both pedigrees: a 3.0-fold increase caused by $\text{Mtrr}^{+/{gt}}$ mothers ($P = 0.066$) and a 4.4-fold increase caused by $\text{Mtrr}^{+/{gt}}$ fathers ($P = 0.03$) relative to controls (Fig. 8A). The former result was not statistically significant. However, hypercellular bone marrow was observed only in wildtype F1 females from an $\text{Mtrr}^{+/{gt}}$ mother ($P = 0.006$; Fig. 8B and C), likely in response to anaemia and increased $\text{Epo}$ expression. This result suggests that the haematopoietic stem cells of F1 females might be more sensitive to maternal rather than paternal heterozygosity. Yet in contrast to older $\text{Mtrr}^{gt/gt}$ females (Fig. 1A and D), reticulocyte counts and reticulocyte production indices were unaltered by a parental effect (Fig. 7A and D). This may indicate that the effects of parental $\text{Mtrr}^{gt}$ heterozygosity are less severe than intrinsic $\text{Mtrr}$ deficiency.

The WBC population and myeloid lineages beyond erythrocytes were not significantly affected in F1 females by an $\text{Mtrr}^{+/{gt}}$ parental genotype (Fig. 7F–L). Although there was no significant increase in the number of Howell–Jolly bodies present in the erythrocytes of the wildtype F1 females regardless of pedigree (Fig. 7E), maternal heterozygosity was associated with the appearance of codocytes (target cells) in at least one of the wildtype F1 females assessed (Fig. 7B). Codocytes were not apparent in $\text{Mtrr}^{gt/gt}$ mice or wildtype F1 females derived from $\text{Mtrr}^{+/{gt}}$ fathers (Figs 1B, 2B and 7B), and are often indicative of liver disease, iron deficiency, or splenic defects (Mehta, 2007). Altogether, these data reveal a parent-specific effect of abnormal folate metabolism such that wildtype females of $\text{Mtrr}^{+/{gt}}$ mothers displayed normocytic anaemia and wildtype females of $\text{Mtrr}^{+/{gt}}$ fathers exhibited RBC microcytosis.

**A parental effect of the $\text{Mtrr}^{gt}$ allele on F1 female spleen histology is not evident**

Unlike $\text{Mtrr}^{gt/gt}$ females, spleen weight and gross histology was normal in wildtype F1 females from either pedigree compared to C57Bl/6 controls (Fig. 8D–I) with the exception of the white pulp cell density, which was slightly increased in F1 females derived from an $\text{Mtrr}^{+/{gt}}$ mother ($P = 0.01$; Fig. 8J). Despite this, $\text{Ki67}^{+}$ cells appeared at a normal frequency in the white and red pulp of these F1 females compared to controls (Fig. 8J and L). However, paternal $\text{Mtrr}^{gt}$ heterozygosity was associated with a slightly higher percentage of mitotic cells in the red pulp of spleens from wildtype F1 females ($P = 0.04$; Fig. 8J and L) yet no clear regions of extramedullary haematopoiesis were observed. Furthermore, the spleens of F1 females from both pedigrees displayed normal iron deposition (Fig. 8K and M) suggesting an absence of excessive haemolysis. Altogether, these data indicate that parental $\text{Mtrr}^{gt}$ heterozygosity does not lead to overt splenic defects including extramedullary erythropoiesis or fibrosis.

**Discussion**

We have shown here that abnormal metabolism of folate caused by the $\text{Mtrr}^{gt}$ mutation in mice results in haematopoietic phenotypes that are sex and age dependent. More specifically, $\text{Mtrr}^{gt/gt}$ female mice displayed macrocytic anaemia, which may be due to defective erythroid differentiation at the exclusion of haemolysis. This was accompanied by robust induction of renal $\text{Epo}$ mRNA expression, hypercellular bone marrow and extramedullary haematopoiesis. In contrast, the male response to abnormal folate metabolism differed since $\text{Mtrr}^{gt/gt}$ male mice were not anaemic but did display erythrocytic macrocytosis and lymphopenia. Regardless of sex, these blood phenotypes developed with age, as the haematopoietic profiles of young $\text{Mtrr}^{gt/gt}$ mice were largely normal though subtle erythrocyte abnormalities hint at an early, milder defect. Remarkably, we also showed that when a parent is a carrier of the $\text{Mtrr}^{gt}$ allele, it resulted in haematological defects in their wildtype adult daughters. However, the type of defect was dependent upon the sex of the parent. Maternal $\text{Mtrr}^{gt}$ heterozygosity resulted in normocytic anaemia with increased renal $\text{Epo}$ and hypercellular bone marrow in wildtype daughters. In this case, it was unclear whether erythrocytic differentiation or longevity was affected. In contrast, paternal $\text{Mtrr}^{gt}$ heterozygosity caused erythrocytic microcytosis not associated with anaemia despite increased renal $\text{Epo}$ mRNA expression in wildtype
daughters. Altogether, our data show that abnormal folate metabolism affects haematopoiesis in an age-, sex- and parent-of-origin-specific manner.

Humans that are folate deficient or carry mutations in genes encoding for folate uptake (e.g. SLC46A1) or metabolism (e.g. MTR, MTRR) exhibit megaloblastic anaemia, a type of macrocytic anaemia (Gulati et al. 1996; Leclerc et al. 1996; Zavadakova et al. 2002; Vilaseca et al. 2003). An important diagnostic criterion for megaloblastic anaemia is the presence of neutrophils with hyper-segmented nuclei (Doig, 2007). While mature neutrophils in mice are fully segmented, natural twisting and folding of their nuclei makes it difficult to distinguish folds from segments (Zhou et al. 2015). Slc46a1−/− mice were found to have macrocytic anaemia with multi-lobed polymorphonuclear neutrophils (Salojin et al. 2011). Even though Mtrrgt/gt female mice display macrocytic anaemia, we were unable to determine whether the anaemia fulfils megaloblastic status. Furthermore, our finding that older Mtrrgt/gt female mice have increased reticulocyte counts contrasts most human cases of megaloblastic anaemia associated with folate deficiency wherein reticulocyte numbers are usually low (Koury & Ponka, 2004). The difference might be explained by type of insult or the species assessed. Regardless, the Mtrrgt females mouse line is a novel model to assess the role of folate metabolism in anaemia.

Clear similarities exist between the haematological phenotypes of known mouse models of folate deficiency/defective folate uptake (Bills et al. 1992; Koury et al. 1997; Zhao et al. 2001; Salojin et al. 2011) and abnormal folate metabolism in the Mtrrgt model (this study). All models display anaemia associated with increased erythropoietin expression, increased erythroid progenitors, and splenomegaly associated with extramedullary haematopoiesis. Hypercellular bone marrow was only observed in Mtrrgt mice (this study) and Slc46a1−/− mice (Salojin et al. 2011). In folate-deficient mice or in Slc46a1 mutants, erythropoiesis fails during the maturation phase and anaemia may be due to increased haemolysis of differentiating erythrocytes (Koury et al. 1997; Salojin et al. 2011). This differs with the Mtrr model where erythrocyte differentiation and/or maturation were abnormal, yet erythroid apoptosis as a contributor to anaemia was unlikely since iron deposition and Hmp1 mRNA expression were normal. This inconsistency may reflect a difference in methodology or in the severity of the initiating defect. For example, the Slc46a1 mutation prevents the uptake of folate (Salojin et al. 2011) akin to dietary folate deficiency. In Mtrrgt mice, folate is transported into the cells as usual but its metabolism is abnormal (Elmore et al. 2007). Furthermore, the Mtrrgt allele is a hypomorphic mutation and has a knockdown effect such that in Mtrrgt mice, a wildtype Mtrr transcript is weakly expressed allowing one-carbon metabolism to progress albeit in a significantly reduced capacity (Elmore et al. 2007). Therefore, the haematological phenotype in Mtrrgt mice is different from and/or not as severe as that in Slc46a1−/− mice.

The onset of haematopoietic defects associated with abnormal folate uptake or metabolism varies between models and also likely depends upon the severity of the disruption. For instance, mouse embryos lacking SLC19A1, another protein that mediates folate uptake (also known as RFC1), die at mid-gestation with a discernable absence of erythropoiesis (Gelineau-van Waes et al. 2008). When rescued from embryonic lethality by maternal folic acid supplementation, Slc19a1−/− mutants die shortly after birth due to an absence of haematopoiesis in the bone marrow, spleen and liver (Zhao et al. 2001), which might implicate regulatory defects in the placenta and fetal liver (Mikkola et al. 2005). Although the timing of phenotypic onset is unknown, Slc46a1−/− mice display severe macrocytic anaemia by 4–6 weeks (Salojin et al. 2011). On the other hand, Mtrrgt female mice do not display macrocytic anaemia until a later stage. Yet, as early as 7 weeks of age, Mtrrgt females exhibit a milder phenotype including increased renal Epo mRNA expression and erythroidic defects (e.g. more Howell–Jolly bodies). This suggests that blood health decreases with age in response to Mtrr deficiency. Overall, folate metabolism appears to play a role in embryonic and adult haematopoiesis.

It was hypothesized that folate-deficient erythroid progenitors are unable to withstand the rapid proliferation that occurs during their formation and, ultimately, undergo apoptosis leading to anaemia (Koury et al. 1997). Anaemia associated with folate deficiency was previously attributed to a lack of thymidylate synthesis resulting in uracil misincorporation into DNA and increased DNA breaks (Wickramasinghe & Fida, 1994; Blount et al. 1997). Others have shown that folate levels and DNA uracil content do not correlate in RBCs of folate-deficient mice, though increased micronuclei formation was detected indicating the presence of chromosomal damage (Swayne et al. 2012). Female and male Mtrrgt mice at both ages assessed had a high frequency of Howell–Jolly bodies (i.e. DNA remnants). Whether these bodies indicate chromosomal instability or an inability to undergo nuclear extrusion during the maturation in erythroid precursor cells is unclear. Certainly, other periods of rapid proliferation, such as fetoplacental development, require folate since embryonic lethality occurs with varying degrees of penetrance in mouse models of defective folate uptake or metabolism (Piedrahita et al. 1999; Swanson et al. 2001; Gelineau-van Waes et al. 2008; Padmanabhan et al. 2013). Whether uracil misincorporation and/or genetic instability are the primary cause of developmental phenotypes has not yet been pursued in these models.

© 2018 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society
An alternative hypothesis to genetic instability as a cause for macrocytic anaemia in Mtrrgt/gt female mice is epigenetic instability. DNA methylation patterns are dynamic during haematopoietic stem cell commitment and differentiation into the erythroid lineage (Madzo et al. 2014). Particularly, the binding sites of GATA2 and RUNX1 among other transcription factors that are known regulators of erythroid differentiation gain 5-hydroxymethylcytosine as differentiation occurs (Madzo et al. 2014). Interestingly, blood phenotypes occur in a number of mouse models with defective regulation of DNA methylation (Tefferi et al. 2009; Ko et al. 2010; Sasaki et al. 2012; Russler-Germain et al. 2014; Kunimoto et al. 2017). For example, a loss-of-function mutation in the mouse gene Aid, which encodes a critical enzyme involved in active DNA demethylation, results in DNA hypermethylation, an expansion of myeloid cells, and reduced erythroid progenitors resulting in anaemia (Kunimoto et al. 2017). Importantly, folate metabolism is required for the transmission of one-carbon methyl groups for cellular methylation (Jacob et al. 1998; Ghandour et al. 2002) including DNA and histone methylation. Global DNA hypomethylation and locus-specific dysregulation of DNA methylation in association with the misexpression of genes occurs in Mtrrgt/gt tissue (Padmanabhan et al. 2013). Therefore, it is possible that a similar dysregulation of DNA methylation occurs in the erythroid lineage affecting its differentiation, maturation and/or potential for survival. The effects of epigenetic instability caused by abnormal folate metabolism on haematopoiesis should be pursued in future studies. Notably, genetic instability and epigenetic instability due to folate deficiency or abnormal folate metabolism need not be mutually exclusive mechanisms.

Prior to this study, there was no clear evidence of a sexually dimorphic response to folate deficiency in humans or mice with respect to anaemia. While only folate-deficient female mice have been assessed for haematological effects (Bills et al. 1992; Koury et al. 1997), the phenotypic data from Slek46a1−/− female and male mice was pooled (Salojin et al. 2011). We showed here that even though both female and male Mtrrgt/gt mice exhibit similar haematological phenotypes (e.g. macrocytic erythrocytes, more Howell–Jolly bodies), their phenotypes at large were unequal since only Mtrrgt/gt females exhibited anaemia associated with increased Epo mRNA expression, splenomegaly and extramedullary haematopoiesis, and only Mtrrgt/gt males exhibited lymphopenia. Apart from blood, only two other sex-specific adult phenotypes have been identified in Mtrrgt/gt mice (Elmore et al. 2007; Padmanabhan et al. 2013). Male Mtrrgt/gt mice display lower plasma total homocysteine levels than Mtrrgt/gt females (Padmanabhan et al. 2013). Whether the concentration of plasma total hyperhomocysteine influences the haematopoietic profile in Mtrrgt/gt mice in a sexually dimorphic manner, if at all, is unknown. Additionally, adult Mtrrgt/gt males showed reduced weight gain over time compared to wildtype littersmates, a phenotype not observed in Mtrrgt/gt females (Elmore et al. 2007). This, together with the observations in this study, implies that some metabolic and physiological responses to Mtrr deficiency are sex specific.

The appearance of anaemia in Mtrrgt/gt female mice and not males might be attributed to hormonal or epigenetic differences. For instance, the self-renewal rate of haematopoietic stem cells is higher in females and in the presence of oestrogen (Nakada et al. 2014). Oestrogen receptor expression is reduced during folate deficiency in male and female mice (Gao et al. 2012; Yuan et al. 2017). Whilst not yet explored in Mtrrgt/gt mice, it is plausible that Mtrrgt/gt females might be more sensitive to the physiological effects of reduced oestrogen signalling resulting in ineffective haematopoiesis. Alternatively, since folate metabolism promotes methyl group availability, defective folate metabolism may differentially affect the maintenance of DNA methylation patterns in males and females leading to the dysregulation of gene expression in a sexually dimorphic manner. While sexual dimorphism of developmental phenotypes in Mtrrgt/gt conceptuses at mid-gestation was not apparent shortly after DNA methylation patterns are established (Iurlaro et al. 2017; Padmanabhan et al. 2017), it is still possible that DNA methylation profiles are unequally maintained between female and male Mtrrgt/gt conceptuses or adults. Maternal folate supplementation results in the differential methylation of DNA in female and male offspring (Penailillo et al. 2015; Barua et al. 2016; Qian et al. 2016; Caffrey et al. 2018), which implies that intrinsic abnormal folate metabolism may lead to a similar deregulatory effect. Whether sex-specific epigenetic dysregulation in the haematopoietic lineage of the Mtrrgt/gt model results in anaemia is yet to be determined and will require an unbiased whole methylome approach.

It is widely known that maternal folate deficiency increases disease/phenotype risk in their offspring, with neural tube defects as the most publicized example (MRC Vitamin Study Research Group, 1991). Paternal folate deficiency also causes craniofacial and musculoskeletal malformations (Lambrot et al. 2013). Nevertheless, little focus has been placed on the parental effects of abnormal folate uptake or metabolism on adult-onset disease in their offspring. Our study supports the hypothesis that when either parent is a carrier of the Mtrr allele, it is sufficient to cause blood defects in their adult offspring. The appearance of anaemia indicates that a related or similar mechanism may apply to adult-onset disease in young adults. However, Mtrrgt/gt females
had splenomegaly, erythrocytes that were macrocytic, and increased reticulocyte counts, all parameters of which were normal in wildtype F1 females from *Mtrrgt/+* mothers. This suggests that the effects of intrinsic *Mtrr* deficiency are more severe than maternal *Mtrrgt* heterozygosity. In contrast, the wildtype daughters of *Mtrr+/* males showed opposing phenotypes to *Mtrr+/* males including erythocytic microcytosis versus macrocytosis, increased renal *Epo* mRNA levels versus normal levels, and a trend towards lymphocytosis versus lymphopenia, respectively. The above compares the haematological effects of parental *Mtrr+/* heterozygosity with intrinsic *Mtrrgt/* homozygosity. While mice with *Mtrr+/* and *Mtrrgt/* genotypes are not metabolically the same (Elmore et al. 2007; Padmanabhan et al. 2013), it is not possible to assess the offspring of *Mtrrgt/* parents without the potential compounding effect of the offspring’s *Mtrr* genotype. Yet, it is remarkable that one parental *Mtrrgt* allele is sufficient to cause haematological effects in wildtype offspring.

The molecular mechanism behind the parental inheritance of blood phenotypes in the *Mtrrgt* mouse model is not well understood and likely differs to some extent depending on which parent is the *Mtrrgt* heterozygote. Folate metabolism is normal in the wildtype F1 generation as determined by normal plasma total homocysteine levels indicating that the metabolic defect lies solely with the parent. Abnormal folate metabolism may lead to the inheritance of de novo DNA mutations and/or defective epigenetic factors (e.g. DNA methylation, protamine/histone methylation, non-coding RNAs) with the potential to alter gene expression and cause an adult phenotype(s) in their wildtype offspring, as others have described in non-folate-related models (Blake & Watson, 2016; Chen *et al.* 2016; Huypens *et al.* 2016). Whole genome, methylome and transcriptome studies in the bone marrow of *Mtrrgt/+* parents and their wildtype daughters will reveal inherited de novo genetic mutations or epigenetic targets that cause anaemia or macrocytosis. A maternal effect of the *Mtrrgt* mutation also implicates an atypical uterine environment during fetal development of the wildtype F1 generation or abnormal milk content. The nature of the epigenetic and physiological abnormalities in pregnant *Mtrrgt/+* females that have the potential to cause late-onset haematological defects in the adult F1 generation are yet to be explored, but anaemia during pregnancy and lactation, itself, might play a role. Beyond this study, it will become important to explore parental folate status or parental mutations in folate-related genes in patients to determine the cause of unexplained anaemia.

**References**

Arosio P, Carmona F, Gozzelino R, Maccarinelli F & Poli M (2015). The importance of eukaryotic ferritins in iron handling and cytoprotection. *Biochem J* **472**, 1–15.

Bannerman RM (1983). Hematology. In *The Mouse in Biomedical Research*, 1st edn, ed. Foster HL, Small JD & Fox JG, pp. 293–312. Academic Press, New York.

Barua S, Kuizon S, Brown WT & Junaid MA (2016). DNA methylation profiling at single-base resolution reveals gestational folic acid supplementation influences the epigenome of mouse offspring cerebellum. *Front Neurosci* **10**, 168.

Bills ND, Koury MJ, Clifford AJ & Dessypris EN (1992). Ineffective hematopoiesis in folate-deficient mice. *Blood* **79**, 2273–2280.

Blake GE & Watson ED (2016). Unravelling the complex mechanisms of transgenerational epigenetic inheritance. *Curr Opin Chem Biol* **33**, 101–107.

Blount BC, Mack MM, Wehr CM, MacGregor JT, Hiatt RA, Wang G, Wickramasinghe SN, Eversion RB & Ames BN (1997). Folate deficiency causes uracil misincorporation into human DNA and chromosome breakage: implications for cancer and neuronal damage. *Proc Natl Acad Sci U S A* **94**, 3290–3295.

Caffrey A, Irwin RE, McNulty H, Strain JJ, Lees-Murdoch DJ, McNulty BA, Ward M, Walsh CP & Pentieva K (2018). Gene-specific DNA methylation in newborns in response to folic acid supplementation during the second and third trimesters of pregnancy: epigenetic analysis from a randomized controlled trial. *Am J Clin Nutr* **107**, 566–575.

Cesta MF (2006). Normal structure, function, and histology of the spleen. *Toxicol Pathol* **34**, 455–465.

Challen GA & Goodell MA (2010). Runx1 isoforms show differential expression patterns during hematopoietic development but have similar functional effects in adult hematopoietic stem cells. *Exp Hematol* **38**, 403–416.

Chen Q, Yan M, Cao Z, Li X, Zhang Y, Shi J, Feng GH, Peng H, Zhang X, Zhang Y, Qian J, Duan E, Zhai Q & Zhou Q (2016). Sperm tsRNAs contribute to intergenerational inheritance of an acquired metabolic disorder. *Science* **351**, 397–400.

Corazza GR, Ginaldi L, Zoli G, Frisoni M, Lalli G, Gasbarrini G & Quaglino D (1990). Howell-Jolly body counting as a measure of splenic function. A reassessment. *Clin Lab Haematol* **12**, 269–275.

Doig K (2007). Anemias caused by defects of DNA metabolism. In *Hematology: Clinical Principles and Applications*, 3rd edn, ed. Rodak BF, Fritsma GA & Doig K, pp. 248–258. Saunders Elsevier, St Louis, MO, USA.

Dore LC & Crispino JD (2011). Transcription factor networks in erythroid cell and megakaryocyte development. *Blood* **118**, 231–239.

Elmore CL, Wu X, Leclerc D, Watson ED, Bottiglieri T, Krupenko NI, Krupenko SA, Cross JC, Rozen R, Gravel RA & Matthews RG (2007). Metabolic derangement of methionine and folate metabolism in mice deficient in methionine synthase reductase. *Mol Genet Metab* **91**, 85–97.

Erlacher M, Grunert SC, Cseh A, Steinfeld R, Salzer U, Lausch E, Nosswitz U, Duckers G, Niehues T, Ehl S, Niemeyer CM & Speckmann C (2015). Reversible pancytopenia and immunodeficiency in a patient with hereditary folate malabsorption. *Pediatr Blood Cancer* **62**, 1091–1094.

Ganz T & Nemet E (2012). Hepcidin and iron homeostasis. *Biochim Biophys Acta* **1823**, 1434–1443.
Gao R, Ding Y, Liu X, Chen X, Wang Y, Long C, Li S, Guo L & He J (2012). Effect of folate deficiency on promoter methylation and gene expression of Esr1, Cdh1 and Pgr, and its influence on endometrial receptivity and embryo implantation. *Hum Reprod* **27**, 2756–2765.

Gelineau-van Waes J, Heller S, Bauer LK, Wilberding J, Maddox JR, Aleman F, Rosenquist TH & Finnell RH (2008). Embryonic development in the reduced folate carrier knockout mouse is modulated by maternal folate supplementation. *Birth Defects Res A Clin Mol Teratol* **82**, 494–507.

Ghandour H, Lin BF, Choi SW, Mason JB & Selhub J (2002). Lymphocyte DNA methylation in postmenopausal women. *J Nutr***132**, 1357–1360.

Gillich A, Bao S, Grabole N, Hayashi K, Trotter MW, Pasque V, Ko M, Huang Y, Jankowska AM, Pape UJ, Tahiliani M, Grundy J (2015). Principles and standards for reporting animal experiments in *The Journal of Physiology and Experimental Physiology*. *J Physiol***593**, 2547–2549.

Gulati S, Baker P, Li YN, Fowler B, Kruger W, Brody LC & Banerjee R (1996). Defects in human methionine synthase in cblG patients. *Hum Mol Genet* **5**, 1859–1865.

Huygens P, Sass S, Wu M, Dyckhoff D, Tschop M, Theis F, Marschall S, Hrabe de Angelis M & Beckers J (2016). Epigenetic germine inheritance of diet-induced obesity and insulin resistance. *Nat Genet***48**, 497–499.

Iurlaro M, von Meyenn F & Reik W (2017). DNA methylation homeostasis in human and mouse development. *Curr Opin Genet Dev***14**, 101–109.

Jacob RA, Grett DM, Taylor PC, James SJ, Passke V, Pogribny IP, Sasy S, Wu M, Dyczkoff D, Yonan H, Lepore JB, Macrae T, Dusznyski R, Shih AH, Song CX, Yu M, Yu Y, Grossman R, Raumann B, Verma A, He C, Levine RL, Lavelle D, Lahn BT, Wickrema A & Godley LA (2014). Hydroxymethylation at gene regulatory regions directs stem/early progenitor cell commitment during erythropoiesis. *Cell Rep***6**, 231–244.

Kaki K, Yamagata T, Asai T, Yamazaki I, Oda H, Hirai H & Mitani K (2005). Dysplastic definitive hematopoiesis in AML1/ETO knock-in embryos. *Blood***106**, 2147–2155.

Mehta R (2007). Anemias: Red blood cell morphology and approach to diagnosis. In *Hematology: Clinical Principles and Applications*, 3rd edn, ed. Rodak BF, Fritsma GA & Doig K, pp. 219–231. Saunders Elsevier, St Louis, MO, USA.

Menzies RC, Crossen PE, Fitzgerald PH & Gunz PW (1966). Cytogenetic and cytochemical studies on marrow cells in B12-deficiency and folate deficiency. *Blood***28**, 581–594.

Mikkola HK, Gekas C, Orkin SH & Dieterlen-Lievre F (2005). Placenta as a site for hematopoietic stem cell development. *Exp Hematol***33**, 1048–1054.

MRC Vitamin Study Research Group (1991). Prevention of neural tube defects: results of the Medical Research Council Vitamin Study. *MRC Vitamin Study Research Group*. *Lancet***338**, 131–137.

Nakada D, Oguro H, Levi BP, Ryan N, Kitano A, Saitoh Y, Takeichi M, Wendt GR & Morrison SJ (2014). Oestrogen increases haematopoietic stem-cell self-renewal in females and during pregnancy. *Nature***505**, 555–558.

North TE, de Brujin MF, Stacy T, Talebian L, Lind E, Robin C, Binder M, Dzierzak E & Speck NA (2002). Runx1 expression marks long-term repopulating hematopoietic stem cells in the midgestation mouse embryo. *Immunity***16**, 661–672.

Padmanabhan N, Jia D, Geary-Joo C, Wu X, Ferguson-Smith AC, Fung E, Bieda MC, Snyder FF, Gravel RA, Cross JC & Watson ED (2013). Mutation in folate metabolism causes epigenetic instability and transgenerational effects on development. *Cell***155**, 81–93.

Padmanabhan N, Rakoczy J, Kondratowicz M, Menelaou K, Blake GET & Watson ED (2017). Multigenerational analysis of sex-specific phenotypic differences at midgestation caused by abnormal folate metabolism. *Environ Epigenet***3**, dxv014.

Patel N, Masaratana P, Diaz-Castro J, Latunde-Dada GO, Qureshi A, Lockyer P, Jacob M, Arno M, Matak P, Mitry RR, Hughes RD, Dhawan A, Patterson C, Simpson RJ & McKie AT (2012). BMPER protein is a negative regulator of hepcidin and is up-regulated in hypotransferrinemic mice. *J Biol Chem***287**, 4099–4106.

Penailillo R, Guajardo A, Llanos M, Hirsch S & Ronco AM (2015). Folic acid supplementation during pregnancy induces sex-specific changes in methylation and expression of the mouse sperm epigenome and is associated with negative pregnancy outcomes. *Nat Commun***4**, 2889.

Leclerc D, Campeau E, Goyette P, Adjalla CE, Christensen B, Ross M, Eydoux P, Rosenblatt DS, Rozen R & Gravel RA (1996). Human methionine synthase: cDNA cloning and identification of mutations in patients of the cblG complementation group of folate/cobalamin disorders. *Hum Mol Genet* **5**, 1867–1874.

Madzo J, Liu H, Rodriguez A, Vasanthakumar A, Sundaravel S, Caces DBD, Looney TJ, Zhang L, Lepore JB, Macrae T, Dusznyski R, Shih AH, Song CX, Yu M, Yu Y, Grossman R, Raumann B, Verma A, He C, Levine RL, Lavelle D, Lahn BT, Wickrema A & Godley LA (2014). Hydroxymethylation at gene regulatory regions directs stem/early progenitor cell commitment during erythropoiesis. *Cell Rep***6**, 231–244.

Low paternal dietary folate alters the mouse sperm epigenome and is associated with negative pregnancy outcomes. *Nat Commun***4**, 2889.
of placental 11β-hydroxysteroid dehydrogenase 2 in rats. PLoS One 10, e0121098.

Piedrahita JA, Oetama B, Bennett GD, van Waes J, Kamen BA, Richardson J, Lacey SW, Anderson RG & Fin nell RH (1999). Mice lacking the folic acid-binding protein Folbp1 are defective in early embryonic development. Nat Genet 23, 228–232.

Prouty HW (1979). Correcting the reticulocyte count. Lab Med 10, 161–163.

Qian YY, Huang XL, Liang H, Zhang ZF, Xu JH, Chen JP, Yuan W, He L, Wang L, Miao MH, Du J & Li DK (2016). Effects of maternal folic acid supplementation on gene methylation and being small for gestational age. J Hum Nutr Diet 29, 643–651.

Rosen CJ, Ackert-Bicknell C, Rodriguez JP & Pino AM (2009). Marrow fat and the bone microenvironment: developmental, functional, and pathological implications. Crit Rev Eukaryot Gene Expr 19, 109–124.

Russell ES & Meier H (1968). Blood and blood formation. In Biological of the Laboratory Mouse, 2nd edn, ed. Green EL. Dover Publications, New York.

Russler-Germain DA, Spencer DH, Young MA, Lamprecht TL, Miller CA, Fulton R, Meyer MR, Erdmann-Gilmore P, Townsend RR, Wilson RK & Ley TJ (2014). The R882H DNMT3A mutation associated with AML dominantly inhibits wild-type DNMT3A by blocking its ability to form active tetramers. Cancer Cell 25, 442–454.

Salojin KV, Cabrera RM, Sun W, Chang WC, Lin C, Duncan L, Platt KA, Read R, Vogel P, Liu Q, Finnell RH & Oravec ZT (2011). A mouse model of hereditary folate malabsorption: deletion of the PCFT gene leads to systemic folate deficiency. Blood 117, 4895–4904.

Sasaki M, Knobbe CB, Munger JC, Lind EF, Brenner D, Brustle O, Sadowin KV, Cabrera RM, Sun W, Chang WC, Lin C, Duncan L, Platt KA, Read R, Vogel P, Liu Q, Finnell RH & Oravec ZT (2011). A mouse model of hereditary folate malabsorption: deletion of the PCFT gene leads to systemic folate deficiency. Blood 117, 4895–4904.

Additional information

Competing interests

None declared.

Author contributions

This work was performed in the Department of Physiology, Development and Neuroscience at the University of Cambridge located in Cambridge, UK. All authors designed and conducted the research, analysed the data, and wrote and edited the manuscript. E.D.W. has primary responsibility for content. All authors read and approved the final manuscript and agree to be accountable for all aspects of the work. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

© 2018 The Authors. The Journal of Physiology published by John Wiley & Sons Ltd on behalf of The Physiological Society
Funding

The work was funded by the Lister Institute for Preventative Medicine, a Next Generation Fellowship from the Centre for Trophoblast Research, the Returning Carer’s grant scheme (Cambridge) and an Isaac Newton Trust/Wellcome Trust ISSF/University of Cambridge joint research grant (to E.D.W.). The following financial support was given: Centre for Trophoblast Research Graduate Studentship (to N.P.), Newnham College (Cambridge) studentship and A.G. Leventis scholarship (to K.M.), H.E. Durham Fund grant and Downing College (Cambridge) summer studentship (to J.G.), and 4-year Wellcome Trust PhD studentship in Developmental Mechanisms (to G.E.T.B.).

Author’s present address

N. Padmanabhan: Department of Cancer and Stem Cell Biology, Duke-NUS Medical School, Singapore.