Human parvovirus 4 ‘PARV4’ remains elusive despite a decade of study [version 1; peer review: 3 approved]

Philippa C. Matthews¹,², Colin Sharp³, Peter Simmonds¹, Paul Klenerman¹,²,⁴

¹Nuffield Department of Medicine, University of Oxford, Peter Medawar Building for Pathogen Research, South Parks Road, Oxford, OX1 3SY, UK
²Department of Infectious Diseases and Microbiology, Oxford University Hospitals NHS Foundation Trust, John Radcliffe Hospital, Headley Way, Headington, Oxford, OX3 9DU, UK
³Roslin Institute, University of Edinburgh, Easter Bush, Midlothian, EH25 9RG, UK
⁴NIHR Biomedical Research Centre, John Radcliffe Hospital, Headley Way, Headington, Oxford, OX3 9DU, UK

Abstract
Human parvovirus 4 (‘PARV4’) is a small DNA tetraparvovirus, first reported in 2005. In some populations, PARV4 infection is uncommon, and evidence of exposure is found only in individuals with risk factors for parenteral infection who are infected with other blood-borne viruses. In other settings, seroprevalence studies suggest an endemic, age-associated transmission pattern, independent of any specific risk factors. The clinical impact of PARV4 infection remains uncertain, but reported disease associations include an influenza-like syndrome, encephalitis, acceleration of HIV disease, and foetal hydrops. In this review, we set out to report progress updates from the recent literature, focusing on the investigation of cohorts in different geographical settings, now including insights from Asia, the Middle East, and South America, and discussing whether attributes of viral or host populations underpin the striking differences in epidemiology. We review progress in understanding viral phylogeny and biology, approaches to diagnostics, and insights that might be gained from studies of closely related animal pathogens. Crucial questions about pathogenicity remain unanswered, but we highlight new evidence supporting a possible link between PARV4 and an encephalitis syndrome. The unequivocal evidence that PARV4 is endemic in certain populations should drive ongoing research efforts to understand risk factors and routes of transmission and to gain new insights into the impact of this virus on human health.

Keywords
Human parvovirus 4, PARV4, PARV4 phylogeny, PARV4 biology, tetraparvovirus
**Introduction**

Human parvovirus 4 (‘PARV4’) was first described in 2005, but many important features of its epidemiology, transmission, and clinical significance remain elusive. PARV4 is a small non-enveloped, single-stranded DNA virus with a genome of approximately 5 kb, translated as two major and two minor open reading frames. Classified as a member of the genus *Tetraviravirus*, in the family *Parvoviridae* (sub-family *Parvovirinae*), it sits phylogenetically alongside porcine and bovine hokoviruses, while its closest human-tropic relatives are well-characterised *B19V* (genus *Erythroparvovirus*) and human bocaviruses (genus *Bocavirus*) (Table 1).

Ongoing investigation of PARV4 is being driven mainly by several intriguing features of its distribution: it is endemic in certain geographic areas, but elsewhere is found confined only to certain high-risk groups. The first reported identification of PARV4 was from an injecting drug user with hepatitis B virus (HBV) infection, who was screened for viral infections following presentation with influenza-like symptoms. Based on this index case, subsequent studies in North America and Western Europe focused mainly on groups with risk factors for parenteral infection and those infected with other blood-borne viruses (BBVs). In these settings, a clear picture has emerged in which PARV4 infections are consistently and strongly associated with HIV, HBV and HCV, mostly in the setting of persons who inject drugs (PWIDs) and those with a history of multiple transfusion. Despite attempts to identify it outside this setting, infection has not been detected in household contacts of seropositive individuals and is infrequent in the general population.

However, groups working in Africa have reported a completely different population epidemiology: in this setting, the detection frequency of PARV4 IgG (indicative of current or past exposure) ranges from 30% to 50% in the general population, without any consistent relationship with BBVs. Acute infections associated with viraemia were detected at a frequency of 8.5% among young children in Ghana.

The clinical syndromes that have been described in association with PARV4 are summarised in Table 1 and Figure 1. However, there are too few data to make any of these associations secure, and attributing causality in a robust way is inevitably challenging.

This article seeks to summarise recent advances that have been made in understanding and characterising the epidemiology, immunology, phylogeny, and pathophysiology of PARV4. We have maintained a primary focus on updates made since our previous review of the topic in 2014, although we have also drawn upon some older references where they are fundamental in supporting our current understanding. Crucially, there are still many gaps in the story; therefore, we have also set out to identify and highlight important questions for future study.

**New advances in the PARV4 literature**

**Population prevalence of infection in different geographic locations**

The most substantial updates to the PARV4 literature are studies to determine the prevalence of infection in geographic areas that had not previously been represented. This includes new studies in Scandinavia, the Middle East, and South America; we have summarised these data in Table 2. Below, we discuss these findings with further reference to their applicability to understanding risk factors for infection.

**Risk factors for PARV4 infection**

Based on the strong relationship between PARV4 and HIV, HBV, and HCV co-infection in North American and European populations, several studies have compared PARV4 exposure (screening for PARV4 IgG or DNA or both) in HIV-positive and HIV-negative groups in different settings. In Iran, HIV infection (with or without HCV co-infection) was reported to be associated with a high prevalence of PARV4 viraemia (35%). However, in this study, the background prevalence of viraemia in healthy blood donors was also high at 17%. Higher seroprevalence was also reported in Scandinavian subjects in the setting of HIV infection; the PARV4 IgG detection frequency was 8% among HIV-positive children.

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**Table 1. Potential and confirmed disease associations of parvoviruses in human and animal hosts.**

| **Parvovirus B19** | **Bocaviruses** | **Bovine and porcine hokoviruses** | **Human parvovirus 4 (‘PARV4’)** |
|-------------------|----------------|----------------------------------|---------------------------------|
| Childhood rash and fever | Respiratory infections, predominately in children | Wasting syndromes | Influenza-like symptoms |
| Inflammatory and autoimmune sequelae, including myocarditis, arthritis, and glomerulonephritis | | Foetal infection/abortion | Encephalitis |
| Myelosuppression leading to anaemia and intra-uterine hydrops | | Diarrhoea | Transient rash and hepatitis |
| Rarely encephalitis | | Skin disease | Foetal hydrops |
| | | Arthritis | Transmission via respiratory secretions or faeces suggestive of respiratory tract infection or gastroenteritis |
| | | | • Acceleration of progression to AIDS in HIV-infected adults |

The evidence of clinical associations for B19V (left-most column) are robust and consistent, in contrast to those for animal hokoviruses and PARV4, in which the evidence is often at the level of case reports or small case series only and for which replication in other cohorts is lacking. Other parvoviruses (for example, dependoparvoviruses and protoparvoviruses) have also been detected from human samples, but evidence is lacking for pathogenicity.
while the background population seropositivity rate was less than 1% in adults and absent in children\textsuperscript{14,22}. Stratification of risk factors in a French study reported the highest PARV4 prevalence in PWIDs, especially among those who were HIV-infected, but also among men who have sex with men (MSM), particularly those likely to have been exposed in the 1980s\textsuperscript{12}. Our own study of a cohort of mothers and children in Kimberley, South Africa, was comparable to previous reports from sub-Saharan Africa in finding an overall PARV4 seroprevalence of 37% with no evidence that HIV infection was a risk factor\textsuperscript{23}. Although vertical transmission has previously been demonstrated in another setting\textsuperscript{24}, there was no concordance between maternal and child serostatus, suggesting that maternal transmission is probably not a major contributor to the overall burden of infection in South Africa\textsuperscript{11}. The clear trend towards increasing acquisition with age is consistent with a broader environmental source of PARV4 infection.

A potential association between PARV4 exposure and infection with another BBV, human T-cell lymphotrophic virus (HTLV), was described in a Brazilian study\textsuperscript{21}. Among 113 subjects with HTLV-1 infection, seven (6%) were positive for PARV4 DNA, two of whom also had HIV or HCV infection or both. Based on a history of blood transfusion in one of these individuals, it was postulated that this represents the most likely route of acquisition of all three viruses. However, the remaining five cases had no other co-infecting BBVs and no history of injecting drug use or blood transfusion, leading to the conclusion that other transmission routes of PARV4 transmission may also be operating\textsuperscript{21}. Another study published by the same group identified PARV4 viraemia in 2–5% of individuals either donating blood or receiving transfusions of blood products\textsuperscript{20}. Neither of these Brazilian studies screened for PARV4 IgG, so the prevalence of PARV4 exposure in this setting remains unknown\textsuperscript{20,21}.

**Viral biology/Immunology**

PARV4 variants characterised to date fall into three distinct genetic groups (genotypes 1–3) but show relatively restricted sequence variability; in both the non-structural (NS) and capsid-encoding genome regions, there is less than 3% amino acid
| Location of cohort | Characteristics of cohort | Prevalence of PARV4 | PARV4 genotype | Clinical associations | Study |
|-------------------|---------------------------|---------------------|----------------|----------------------|-------|
| **Europe/Scandinavia** |                           |                     |                |                      |       |
| France            | High-risk blood donors and recipients of blood products (including HCV-positive \(n = 216\) and HIV-positive \(n = 314\)) | PARV4 IgG detected in 20% of HCV-positive, 23% of HIV-positive | Not determined | Not reported | Servant-Delmas et al. (2014) |
| Denmark           | HIV-positive children and adolescents (\(n = 46\)); 52% of African origin. | PARV4 IgG detected in 9%; IgM in 2%. PARV4 PCR-negative in all cases. | PCR done but negative in all cases | Lower CD4\(^+\) T-cell counts in PARV4 IgG-positive subjects | Rosenfeldt et al. (2015) |
| Denmark           | Birth cohort of healthy infants at birth (\(n = 176\)) and at 1 year (\(n = 202\)) and mothers (\(n = 228\)) | PARV4 IgG detected in 0.9% of mothers and in 0% of children at birth and at age 1 year | Not determined | Not reported | von Linstow et al. (2015) |
| **Middle East**   |                           |                     |                |                      |       |
| Iran              | HIV-positive (\(n = 133\)) versus healthy blood donors (\(n = 120\)) | PARV4 DNA detected in 35% of HIV-positive and 17% of HIV-negative subjects | Sequences all consistent with genotype-1 | Not reported | Asiyabi et al. (2016) |
| **Africa**        |                           |                     |                |                      |       |
| South Africa      | HIV-positive mothers (\(n = 43\)), HIV-positive children (\(n = 90\)) and their HIV-negative siblings (\(n = 24\)) | PARV4 IgG detected in 37%. Trend towards higher prevalence in adults compared with children. | Not determined | No association between PARV4 status and CD4\(^+\) T count or HIV viral load | Matthews et al. (2015) |
| **Asia**          |                           |                     |                |                      |       |
| Taiwan            | Healthy health-care workers (\(n = 10\)) | PARV4 DNA detected in 60% and IgM in 30% (persistent for 1-year follow-up period) | PCR products identical to a previous sequence\(^{31}\), described as a ‘sub-cluster’ of genotype-2 | Subjects were well or asymptomatic. | Chen et al. (2015) |
| India             | Patients with acute encephalitis syndrome (\(n = 10\)) after exclusion of other causes of viral encephalitis | PARV4 DNA detected in 20% in cerebrospinal fluid | Sequences consistent with genotype-2 | Encephalitis | Prakash et al. (2015) |
| **South America** |                           |                     |                |                      |       |
| Brazil            | Patients with haemophilia (\(n = 28\)), beta-thalassaemia major (\(n = 40\)), and volunteer blood donors (\(n = 68\)) | PARV4 DNA detected in 6% | Genotype of sequences not reported | Not reported | Slavov et al. (2015) |
| Brazil            | HTLV1/2-positive patients (\(n = 130\)) ± HIV, HBV, HCV co-infection | PARV4 DNA detected in 5% (\(n = 1\) with HCV and 1 with HCV/HIV) | Similar to Indian strain (GenBank HQ593532\(^{32}\)) – genotype-2 | Not reported | Slavov et al. (2016) |

HBV, hepatitis B virus; HCV, hepatitis C virus; HIV, human immunodeficiency virus; HTLV, human T-cell lymphotrophic virus; PCR, polymerase chain reaction.
(8–9% nucleotide) sequence divergence between genotypes (representations of diversity can be found in Figure 2 and in Supplementary data 1). The even greater restriction of sequence diversity within genotypes supports the hypothesis for relatively recent transmission to human populations. Relatively few new PARV4 sequences have been reported over the period that we have reviewed, and although incremental additions to the sequence database have been made over recent years (Figure 3), these have not substantially extended the known diversity of this virus.

The distribution of the three genotypes is summarised as follows:

- **Genotype-1** is the genotype currently predominant in Europe and North America\(^1\,\textit{a}^{11}\,\textit{b}^{25}\,\textit{c}^{27}\). Sequencing of PARV4-positive plasma pools and blood products concentrates from various collection years\(^2\,\textit{a}^{28}\,\textit{b}^{29}\) as well as analysis of the age distributions of PARV4-infected study subjects\(^2\,\textit{a}^{26}\) suggests that genotype-1 replaced genotype-2 as the predominantly acquired genotype in these regions from the mid-1990s onwards, analogous to the genotype replacement that has been described for another parvovirus, B19V\(^3\,\textit{a}^{30}\). PARV4 sequences derived from a recent study in Iran also all grouped as genotype-1\(^1\,\textit{a}^{19}\).

- **Genotype-2** (formerly known as PARV5) has been identified in European and North American cohorts\(^1\,\textit{a}^{25}\,\textit{b}^{27}\) and appears to be the more common genotype in individuals likely infected in the 1980s or early 1990s\(^1\,\textit{a}^{11}\,\textit{b}^{26}\). It was also the predominant strain reported from Asia\(^1\,\textit{a}^{31}\,\textit{b}^{32}\). Limited amplification of PARV4 genomes from Brazil\(^2\,\textit{a}^{21}\) yielded sequences that were most similar overall to genotype-2 strains previously identified in India\(^2\,\textit{a}^{33}\).

- **Genotype-3** has been consistently identified from African cohorts\(^1\,\textit{a}^{13}\). We have recently derived full-length PARV4 sequences from an adult and child in South Africa (GenBank accession numbers KU871314 and KU871315), which cluster together with genotype-3 sequences.

Various reports provide preliminary evidence that PARV4 may not be completely cleared after acute infection, suggesting that it has the potential for latency and reactivation. Two studies in Taiwan have sought to describe serological responses to PARV4 infection by undertaking longitudinal follow-up of their cohorts\(^1\,\textit{a}^{31}\,\textit{b}^{33}\). Among a small cohort of health-care workers, IgG seropositivity was strikingly high at 60%; half of these had a
positive IgM that was sustained over the study period, and viremia was detected at one of several sampling time-points. In the second study, this time focusing on a high-risk PWID cohort, IgM was reported as remaining positive for up to 21 months. Meanwhile, in vitro experiments have demonstrated a sustained high-magnitude ex vivo CD8 T-cell response to PARV4 NS peptide. Prolonged IgM-positivity and sustained high-magnitude T-cell responses together suggest a sustained or relapsing/remitting exposure to viral antigen. Tissue homing and sites of latency are unknown, but existing data suggest that bone marrow, the respiratory tract, liver and gut might represent potential sites of viral replication. Skin has also been highlighted as a potential reservoir site for B19V, although—to the best of our knowledge—no study has investigated this as a site of PARV4 replication. The role of capsid proteins in parvovirus infections has been recently reviewed, although there are no specific functional or structural data for PARV4.

Clinical associations of PARV4

To date, determining the clinical impact (if any) of PARV4 infection remains perhaps the most uncertain area of research into this virus, despite the medical importance of establishing such disease associations. A wide range of potential infection outcomes has been proposed (summarised in Table 1), but the evidence for a
A novel polymerase chain reaction (PCR) assay for genotyping and quantifying PARV4 was published in 2014\(^{46}\). The authors report that their method reliably discriminates between PARV4 genotypes, and use quantitative PCR to measure viraemia\(^{46}\).

Practical implications: human tissue for transfusion and transplantation

Consistently high detection frequencies of anti-PARV4 antibodies in sera of haemophiliac individuals provide strong evidence for some transmission via the use of clotting factor concentrates\(^{11,42}\). Although modern procedures for viral inactivation may effectively remove parvovirus infectivity, PARV4 is more robust than B19V to heat and other virus inactivation methods used in blood product manufacture, and there is ongoing discussion about the need to implement donation screening for PARV4 DNA and/or to enhance measures to ensure that the virus is eradicated from blood products for transfusion\(^{10,43-45}\).

Solid organ transplant recipients are a more difficult population to assess and are unsurprisingly less well represented in the literature; no new articles on this topic have been published in the past two years. However, since 2008, an Italian study has reported finding PARV4 in a small number of renal transplant recipients\(^{47}\), and a French cohort of lung transplant patients reports that 14% were viraemic\(^{48}\). The clinical significance of these findings and whether these cases represent reactivation of autologous virus in the context of immunosuppression or transmission of donor virus at the time of organ transplantation have yet to be explored.

Insights from new animal data

There is increasing evidence that infections with porcine and bovine hokoviruses are endemic in both wild and domestic animals; most of these recent animal data are simply detection studies and do not provide any new data about pathogenicity. These include the frequent detection of porcine hokovirus in hunted wild boar in Portugal\(^{49}\) and a bovine hokovirus in domestic yaks\(^{50}\). In South America, another hokovirus was found to be endemic in a survey of Brazilian pig herds, in which post-weaning multisystemic wasting syndrome was common\(^{50}\), and a novel porcine hokovirus (referred to as porcine parvovirus 6, or PPV6) has been associated with foetal loss in pigs in China\(^{11,51}\).

As livestock pathogens, these organisms are potentially implicated as a cause of significant economic losses in agriculture\(^{25,26}\). However, since most of the suggested pathogenicity has been attributed to protoparvoviruses or copiparvoviruses, we cannot necessarily infer any significance to tetraparvoviruses. Nevertheless, the widespread isolation of parvoviruses, particularly from domestic animals, should raise concerns about the potential risk of inter-species transmission events leading to the possibility of more pathogenic viruses crossing into human populations.

Discussion and conclusions

As this review illustrates, our understanding of PARV4 continues to advance gradually, but there are still many important unresolved questions, and the significance of this infection to human health remains uncertain. The striking difference in population epidemiology in developed and developing countries currently remains
unexplained, and it is uncertain to what extent differences in virus properties or host characteristics account for the marked differences in population seroprevalence. For the former, it is plausible that genotype-specific amino acid substitutions underpin differences in the route, mechanism, or efficiency of transmission. From the host side, it is possible that differences in human genetics, prevalent co-infections, or environmental, behavioural, or iatrogenic exposure account for differences in seroprevalence and risk factors between continents.

Ongoing diligent scrutiny of carefully characterised clinical cohorts will be required to cement any associations with human disease; this may require larger collaborative efforts than have been undertaken to date. An in vitro system is still needed to help us understand the biology of PARV4 in more detail, including characterisation of tissue tropism, productivity of cellular infection, the influence of co-infecting viruses, and the mechanisms underlying viral suppression by the immune system.

This review highlights a number of compelling arguments in favour of advancing our understanding of PARV4. Firstly, this agent is endemic in some human populations; even if pathology emerges in only a small subset of infected individuals, this may still be important in terms of overall case numbers. Putative associations with significant pathology may be particularly relevant for certain vulnerable groups, including those with other chronic viral infection (HIV, HBV, or HCV), those with solid organ or bone marrow transplantation, and recipients of human blood or tissue transplant.[1,3].

Secondly, we know that viral infections are relevant to the host in more diverse ways than just the effects of primary infection; they may shape immune ontogeny, influence the outcomes of infection with other pathogens[4, and drive or control oncogenesis. Understanding viral biology also allows us to draw on these agents as a resource for vaccine design, as exemplified by the adenovirus constructs used in vaccine trials for HIV[5,6] and HCV[7].

Therefore, whether PARV4 turns out to be an innocent bystander or an elusive human pathogen, there are robust reasons for advocating ongoing clinical and research efforts to further our understanding of epidemiology and the current and future potential significance to human health.

**Abbreviations**
B19V, parvovirus B19; BBV, blood-borne virus; CSF, cerebrospinal fluid; HBV, hepatitis B virus; HCV, hepatitis C virus; HIV, human immunodeficiency virus; HTLV, human T-cell lymphotrophic virus; NS, non-structural; PARV4, human parvovirus 4; PCR, polymerase chain reaction; PWID, person who injects drugs.

**Competing interests**
The authors declare that they have no competing interests.

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**Supplementary data**
(A) PARV4 ORF-1 amino acid sequence; (B) PARV4 ORF-2 amino acid sequence.

Click here to access the data.

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**References**

1. Jones MB, Kapoor A, Lukashov VV, et al.: New DNA viruses identified in patients with acute viral infection syndrome. J Virol. 2005; 79(13): 8230–6. PubMed Abstract | Publisher Full Text | Free Full Text
2. Matthews PC, Malik A, Simmons R, et al.: PARV4: an emerging tetraparvovirus. PLoS Pathog. 2014; 10(5): e1004036. PubMed Abstract | Publisher Full Text | Free Full Text
3. Lau SK, Woc PC, Tse H, et al.: Identification of novel porcine and bovine parvoviruses closely related to human parvovirus 4. J Gen Virol. 2008; 89(Pt 8): 1840–8. PubMed Abstract | Publisher Full Text
4. Sharp CP, Vermeulen M, Nebie Y, et al.: Changing epidemiology of human parvovirus 4 infection in sub-Saharan Africa. Emerg Infect Dis. 2010; 16(10): 1605–7. PubMed Abstract | Publisher Full Text | Free Full Text
5. Simmons P, Manning A, Kenneil R, et al.: Parenteral transmission of the novel human parvovirus PARV4. Emerg Infect Dis. 2007; 13(9): 1386–8. PubMed Abstract | Publisher Full Text | Free Full Text
6. Pryer JF, Lucas SB, Padley D, et al.: Parvoviruses PARV4/5 in hepatitis C virus-infected patient. Emerg Infect Dis. 2007; 13(1): 175–6. PubMed Abstract | Publisher Full Text | Free Full Text
7. Simmons R, Sharp C, Levine J, et al.: Evolution of CD8+ T cell responses after acute PARV4 infection. J Virol. 2013; 87(6): 3087–96. PubMed Abstract | Publisher Full Text | Free Full Text
8. Simmons R, Sharp C, McClure CP, et al.: Parvovirus 4 infection and clinical outcome in high-risk populations. J Infect Dis. 2012; 205(12): 1816–20. PubMed Abstract | Publisher Full Text | Free Full Text
9. Lucharchaiwong W, Chieochansin T, Payungporn S, et al.: Parvovirus 4 (PARV4) in serum of intravenous drug users and blood donors. Infection. 2008; 36(5): 488–91. PubMed Abstract | Publisher Full Text
10. Maple PA, Beard S, Parry RP, et al.: Testing UK blood donors for exposure to human parvovirus 4 using a time-resolved fluorescence immunoassay to screen sera and Western blot to confirm reactive samples. Transfusion. 2013; 53(10 pt 2): 2575–84. PubMed Abstract | Publisher Full Text | F1000 Recommendation
11. Sharp CP, Lail A, Donfield S, et al.: Virologic and clinical features of primary
elicits cell-mediated immunity but does not affect disease progression in HIV-1-infected male subjects: results from a randomized placebo-controlled trial (the Step study). *J Infect Dis.* 2011; 203(6): 765–72. PubMed Abstract | Publisher Full Text | Free Full Text

57. Barnes E, Folgori A, Capone S, et al.: Novel adenovirus-based vaccines induce broad and sustained T cell responses to HCV in man. *Sci Transl Med.* 2012; 4(115): 115ra1. PubMed Abstract | Publisher Full Text | Free Full Text

58. Taylor S, Lopez P, Weckx L, et al.: Respiratory viruses and influenza-like illness: Epidemiology and outcomes in children aged 6 months to 10 years in a multi-country population sample. *J Infect.* 2017; 74(1): 29–41. PubMed Abstract | Publisher Full Text | F1000 Recommendation

59. Kailasan S, Agbandje-McKenna M, Parrish CR: Parvovirus Family Conundrum: What Makes a Killer? *Annu Rev Virol.* 2015; 2(1): 425–50. PubMed Abstract | Publisher Full Text
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