

Harnessing Individual Participant Data from Clinical Trials to Predict Relapse in Visceral Leishmaniasis



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A thesis submitted for the degree of
Doctor of Philosophy in Clinical Medicine

Hilary 2026

Abstract

Abstract goes here.

Acknowledgements

Personal

Acknowledgements go here. Supervisors, colleagues, friends, family. Also need to acknowledge publications including any shared authorship.

Institutional

Can include financial support here.

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List of Abbreviations

ABD	Amphotericin B deoxycholate
ABLE	Amphotericin B lipid emulsion
ALT	Alanine aminotransferase
AST	Aspartate aminotransferase
AUC	Area under the receiver operating characteristic curve
BPKIHS	B.P. Koirala Institute of Health Sciences
BMGF	Bill & Melinda Gates Foundation
BMI	Body mass index
CD	Cluster of differentiation
CDISC	Clinical Data Interchange Standards Consortium
CI	Confidence interval
CL	Cutaneous leishmaniasis
CRP	C-reactive protein
Crt	Creatinine
DAT	Direct agglutination test
DNDi	Drugs for Neglected Diseases initiative
EC	European Commission
EoT	End of treatment
ESR	Erythrocyte sedimentation rate
FevDur	Fever duration
GDPR	General Data Protection Regulation
HAART	Highly active antiretroviral therapy
Hb	Haemoglobin
HR	Hazard ratio
HIV	Human immunodeficiency virus

ICT	Immunochromatographic test
IDDO	Infectious Diseases Data Observatory
IFNγ	Interferon gamma
IM	Intramuscular
IPD	Individual participant data
IQR	Interquartile range
IRS	Indoor residual spraying
ISC	Indian subcontinent
ITN	Insecticide treated nets
IV	Intravenous
KAEP	Kala-azar Elimination Programme
KAMRC	Kala-azar Medical Research Centre
kDNA	Kinetoplast deoxyribonucleic acid
LAMB	Liposomal amphotericin B (AmBisome [®] ; Gilead Sciences)
LEAP	Leishmaniasis East Africa Platform
LST	Leishmanin skin test
MA	Meglumine antimoniate
MCL	Mucocutaneous leishmaniasis
MF	Miltefosine
MPS	Mononuclear phagocyte system
MSF	Médecins Sans Frontières
NCVBDC	National Centre for Vector Borne Diseases Control
NTD	Neglected tropical disease
PCR	Polymerase chain reaction
PD1	Programmed cell death protein-1
PICOTS	Population, Index Model, Comparator Model, Outcome, Timing, Setting
PK-PD	Pharmacokinetic-pharmacodynamic
Plt	Platelets
PM	Paromomycin
qPCR	Quantitative polymerase chain reaction

RBC	Red blood cell
RDT	Rapid diagnostic test
RMRIMS . . .	Rajendra Memorial Research Institute of Medical Sciences
SDA	Single dose administration
SDTM	Study Data Tabulation Model
SpnSize	Spleen size
SSG	Sodium stibogluconate
TDR	UNICEF/UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases
TGFβ	Transforming growth factor beta
UN	United Nations
UNDP	United Nations Development Programme
UNICEF	United Nations International Children's Emergency Fund
VL	Visceral leishmaniasis
WBC	White blood cells
WHO	World Health Organization

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Introduction

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Background

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2.1 Introduction

This chapter provides important context for the development and validation of prognostic models predicting VL relapse in the Indian subcontinent (ISC) and East Africa. It begins with an overview of VL, outlining its epidemiology, pathophysiology, clinical features, and management. Emphasis is placed on the epidemiology of VL and the ongoing WHO-supported elimination programmes in the ISC and East Africa, defining the public health landscape in which a VL prognostic model would be implemented.

The section on relapse is presented as a narrative synthesis informed by a systematic review of the literature (full methods in Appendix A). Using pre-specified inclusion criteria, the review identifies and evaluates studies describing the burden, mechanisms, and determinants of relapse. The discussion highlights how relapse constitutes a high-risk infection reservoir that, together with PKDL and VL/HIV co-infection, poses a major threat to elimination efforts — a threat that could be mitigated through early identification of patients at high risk of relapse, enabling timely diagnosis and treatment.

2.2 Visceral Leishmaniasis

The leishmaniases are a diverse group of neglected tropical diseases (NTDs) caused by protozoan parasites of the *Leishmania* genus and transmitted between susceptible mammalian hosts via the bite of infected female sandflies[1]. At least 20 *Leishmania* species infect humans, causing four principal disease forms: cutaneous leishmaniasis (CL), mucocutaneous leishmaniasis (MCL), visceral leishmaniasis (VL), and post kala–azar dermal leishmaniasis (PKDL) (see Box 2.1)[1–4]. Disease form is largely determined by parasite species and strain, resulting in a spectrum of clinical presentations ranging in severity from the relatively common and usually self-healing skin lesions seen in CL, to the often disfiguring mucosal destruction of MCL, and life-threatening systemic illness of VL. PKDL is a disseminated dermal eruption that may occur following VL recovery, and while patients are systemically well, they have been shown to be infective to sandflies[3].

VL represents the most severe manifestation of leishmaniasis, accounting for the vast majority of its morbidity and mortality. The disease overwhelmingly affects impoverished rural populations with poor access to healthcare. VL is also recognised as an opportunistic infection in patients living with human immunodeficiency virus (HIV), in whom co-infection leads to particularly high rates of treatment failure and death.

2.2.1 Epidemiology

This section provides an overview of the current global distribution, transmission dynamics, and risk factors for developing visceral leishmaniasis, highlighting major regional differences in disease burden and risk.

VL is endemic¹ in at least 80 countries across tropical, semi-tropical and temperate climes. The disease is caused by two closely related *Leishmania* species whose

¹Defined by the WHO as the occurrence of at least one autochthonous case with demonstrated local transmission within a country[5].

Box 2.1: Principal disease forms of Leishmaniasis[2, 4]

Cutaneous leishmaniasis (CL) Results in lesions on exposed skin that can lead to ulceration and life-long scarring. Often self-healing within a year, but can manifest atypical and disseminated forms, especially in the immunocompromised. Up to 1 million new cases per year with most cases occurring in the Americas, Mediterranean basin, Middle East and Central Asia.

Mucocutaneous leishmaniasis (MCL) Rare complication of CL seen especially in the Americas with most cases reported in Bolivia, Perú, and Brazil. Results in destructive ulceration of the oral and nasal mucosa. Highly stigmatising and challenging to treat.

Visceral leishmaniasis (VL) Also known as kala-azar, the most severe form of leishmaniasis caused by *L. donovani* in the Old World and *L. infantum* in the New World. With an estimated 50,000–90,000 cases/year, VL presents with progressive weight loss, splenomegaly and fever. Considered fatal without treatment.

Post kala-azar dermal leishmaniasis (PKDL) Benign macular and/or papular rash often including the face, arms, and trunk. Affects 5–20% of patients months to years after successful initial treatment for VL in the Indian subcontinent and East Africa. Often self-limiting, although known to be infective to sandflies and therefore acts as a disease reservoir.

distribution defines the four principal global regions of high endemicity (see Figure 2.1): *L. donovani*, responsible for anthroponotic transmission (human→sandfly→human) in the ISC and East Africa, and *L. infantum*², responsible for zoonotic transmission (mammal→sandfly→human) in the Americas (principally Brazil) and Mediterranean basin, extending into the Middle East and Central Asia[5, 6]. Together, these two species comprise the *L. donovani* complex.

²Previously referred to as *L. chagasi* in the Americas.

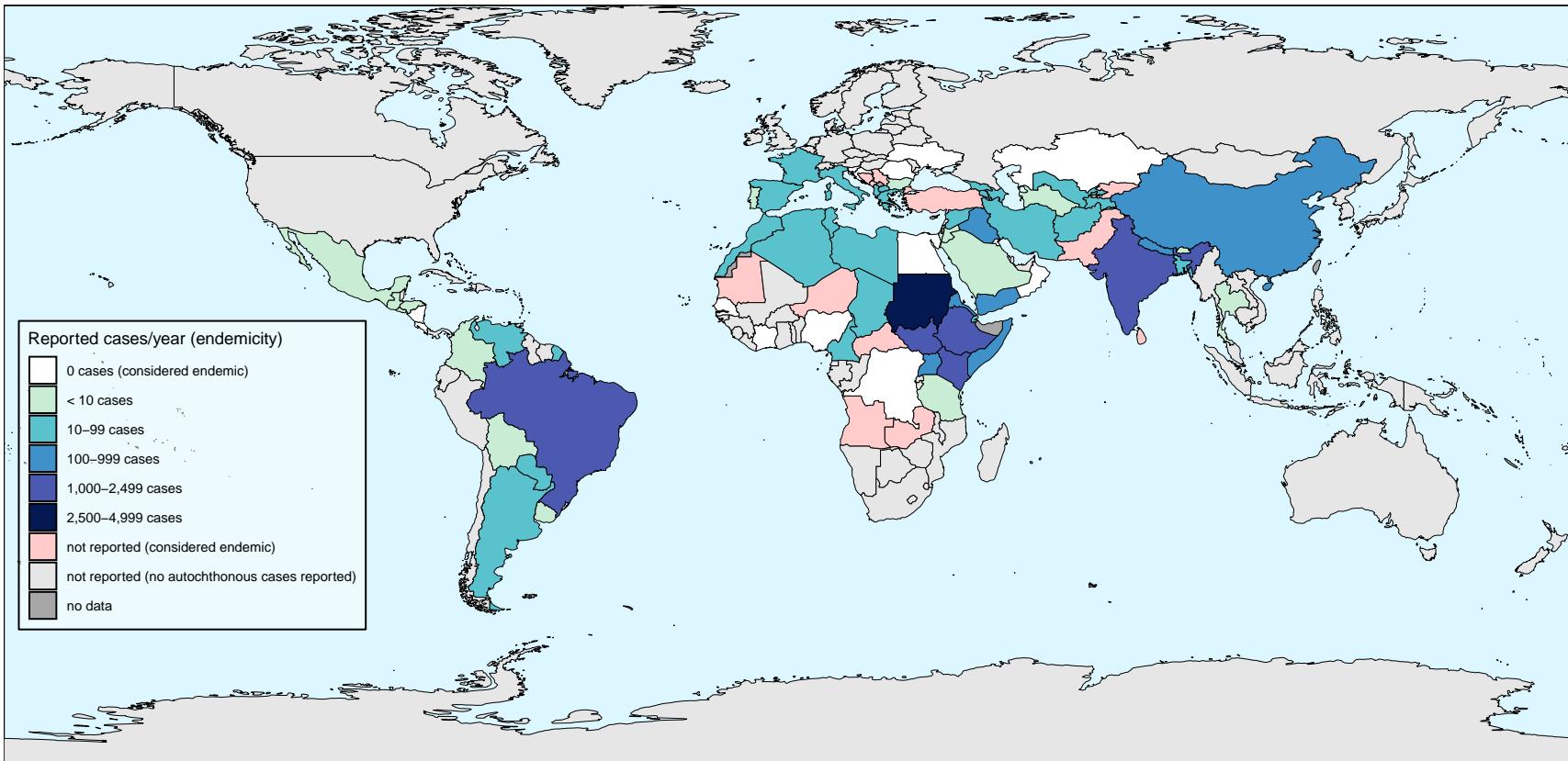


Figure 2.1: Visceral leishmaniasis endemicity (reported 2023) and average annual cases (reported 2018–2023). ‘Considered endemic’ — at least one autochthonous case has been reported, with or without the entire cycle of transmission being demonstrated. Data sourced from the World Health Organization Global Health Observatory, accessed October 2025[6].

Disease Burden

Estimating the global burden of VL is problematic. True case numbers are obscured by significant underreporting due to limited access to healthcare, inadequate diagnostic facilities, misdiagnosis, and poor surveillance systems in many endemic countries[7–10]. In 2012, Alvar et al published the results of a WHO-led update to the global incidence of leishmaniasis using country-level reporting from the mid-late 2000s[11]. Underreporting rates were estimated through consultation with country representatives and disease experts. The global incidence was estimated at 200,000–400,000 cases/year, with approximately 80% of the burden originating from the ISC and 15% from East Africa. Compared to official reporting over the same period, this reflected a global underreporting rate of 3.5–7-fold.

Since the publication of Alvar et al's estimates, the number of cases has undisputedly fallen, driven largely by decreases in the ISC following the launch of the Kala-Azar Elimination Programme (KAEP) in 2005. Reported cases decreased from >50,000 cases/year prior to 2012, to approximately 22,500 cases/year in 2017 and <12,000 cases/year in 2023[6] (high incidence country breakdowns presented in Figure 2.2). Notably, this downward trend has persisted despite improvements in surveillance and reporting systems in many endemic countries[5]. Reflecting these changes, the WHO revised its estimated annual incidence in 2017 to 50,000–90,000 cases/year³[4, 12].

Based on the most recent reporting data from 2023[6], the five countries with the highest case numbers are now, in descending order, Sudan, Ethiopia, Brazil, Kenya and South Sudan — collectively comprising 72.4% of the global total. In stark contrast to the situation 20 years ago, countries in the ISC now account for only 6.3% of the reported total: India with 538 cases (4.6%), Nepal with 168 cases (1.4%), and Bangladesh with just 34 cases (0.3%).

Mortality

The disease is widely described as ‘fatal without treatment’[2, 3]. Supporting this statement are the high mortality figures recorded during conflict-related epidemics in East Africa over the last 40 years, and prior to effective therapy, 19th century accounts of outbreaks devastating communities across the Gangetic plains[13–15]. Despite this, subclinical disease forms have been reported with spontaneous resolution[16, 17].

³According to the online WHO Leishmaniasis Fact Sheet: <https://www.who.int/news-room/fact-sheets/detail/leishmaniasis>. Alternate WHO online content estimates 30,000 cases/year since 2020: <https://www.who.int/health-topics/leishmaniasis> (online material last accessed October 2025).

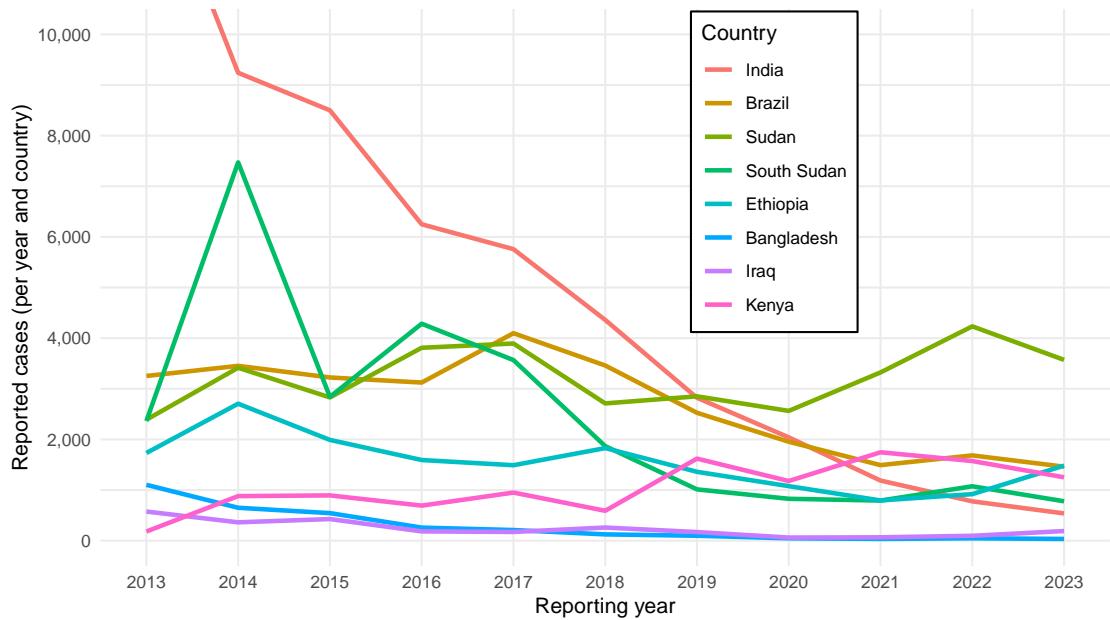


Figure 2.2: Temporal trends of visceral leishmaniasis incidence by country. Comparison between the top 8 countries with the highest average case numbers reported between 2013 and 2023. Data sourced from the World Health Organization Global Health Observatory[6].

With treatment, ~5–15% of cases result in death, although accurate estimates are challenged by a lack of reporting. Where deaths are reported, they frequently only reflect hospital deaths and omit those where a definite diagnosis was missed. In the 2000s, it was often cited that VL was responsible for up to 50,000 deaths/year — the second highest mortality from a parasitic disease after malaria[7] — although more recent estimates tentatively place the figure at a more modest 4,627 deaths/year with a wide uncertainty range of 1,853–8,725 deaths/year[18].

Vector

Measuring 2–4 mm and covered in dense hairs, phlebotomine sandflies (Diptera: Psychodidae) appear distinctly fuzzy under magnification. Females from an estimated 31 species across two genera are known to transmit the parasite between human hosts: *Lutzomyia* in the New World and *Phlebotomine* in the Old World[19]. Sandflies occupy a wide range of ecological niches, found on every continent except Antarctica. Biting occurs from dusk to dawn, with females requiring a blood meal for larval development. During the day they are found in cool and sheltered locations, such as in cracks and crevices in walls as seen with *Ph. argentipes*, responsible for transmission in the ISC. In East Africa, three sandfly vectors have been implicated in *L. donovani* transmission, defining two distinct and non-overlapping ecological settings: (i) the *Acacia-Balanites* and black cotton soil savannah regions in northern

focus, incorporating Sudan, northern South Sudan, and northern Ethiopia, where *Ph. orientalis* thrives, and (ii) the savannah and forested areas in the southern focus, incorporating southern Ethiopia, Kenya, and Uganda, where *Ph. martini* and *Ph. celiae* are seen in association with *Macrotermes* termite mounds.

In addition to sandflies, needle sharing among people who inject drugs was considered an important route of transmission in the southern Mediterranean region during the 1990s and 2000s, particularly among people living with HIV [20]. Exceptionally, transmission can also result from blood transfusion, organ transplantation, laboratory accidents[2], mother-to-child transmission[21], and possibly even sexual contact[22, 23].

Reservoirs

Similar to the majority of *Leishmania* spp. causing CL and MCL, *L. infantum* demonstrates zoonotic transmission, with domestic dogs being the main reservoir host in both the Americas and the Old World. This being said, an ever-increasing list of wild and domestic animals are known to harbour the parasite, including cats, foxes, horses, rodents, bats and opossums, although their relevance to human infection is unclear[24, 25]. An outbreak near Madrid (2009–2012) was attributed to hares[26].

In contrast to *L. infantum*, and importantly from an elimination perspective, *L. donovani* transmission in the ISC and East Africa is predominantly anthroponotic. Xenodiagnosis studies confirm that patients with active VL and those with PKDL are competent human reservoirs, in contrast to individuals with asymptomatic infection[27, 28]. Although *L. donovani* infections have been detected in several animal species in both regions—including cattle, dogs, and rats—their relevance as sources of human transmission remains unproven[29, 30].

Risk Factors

From population prevalence studies we know that only a minority of people with detectable parasites develop symptoms[3, 31]. Risk factors for acquiring an initial asymptomatic infection and subsequent progression to symptomatic disease reflect a tangled ecology of determinants linking host factors (sandfly exposure, immunity, genetics) and parasite factors (strain, virulence, inoculum). A common theme, woven into many of these determinants, is poverty.

In both the ISC and East Africa the median age of infection during stable transmission is similar at 15–20 years. More men than women are infected and develop disease, likely reflecting their increased occupational exposure to sandflies (for example, cattle herding and other outdoor activities)[5].

In the ISC⁴, VL endemicity is centred on the fertile and low-lying alluvial plains of the Ganges river, where high humidity, heavy monsoon rains, and abundant vegetation provide ideal conditions for sustained transmission between sandflies and humans[32]. Significant clustering of cases is seen across the rural farming communities of Bihar, Jharkhand, Uttar Pradesh, and West Bengal in northeastern India, central and western Bangladesh, and southeastern Nepal. In a systematic review by Bern et al., determinants of VL transmission in the ISC included living in mud houses, proximity to prior cases (in the same or nearby household), presence of vegetation and standing water surrounding the house, sleeping on the floor or outside, malnutrition, and a lack of bed net use[33].

The greatest concentration of cases in East Africa is reported in the northern focus, specifically between the eastern Sudanese state of Gederaf and the bordering northern states of Ethiopia. Many of the epidemiological determinants of VL in East Africa are shared with the ISC, with poverty remaining the central overarching factor. Notable determinants include living in rural settings near sandfly breeding and resting sites (living near termite mounds in the southern focus, sleeping under *Acacia* trees in the northern focus), living in proximity to other VL infected (or recently infected) people, and malnutrition[34].

VL/HIV co-infection has reshaped VL epidemiology in many endemic regions, and remains the most important risk factor for asymptomatic infection, disease progression, and poor treatment outcomes. In the mid-1980s in Spain and other southern European countries, VL shifted from a rare childhood disease to one predominantly affecting HIV-positive adults[35, 36]. VL/HIV co-infection rates are currently increasing in Brazil (now reported in 20% of new cases[37]) and India (>10% of VL episodes in 2023 and 2024[38]). In northern Ethiopia, VL/HIV co-infection presents a significant challenge to elimination, affecting between 20 and 50% of cases predominantly in male migrant workers[39].

Host immunity — particularly cell-mediated immunity — is a major determinant of disease onset and treatment outcomes, and thought to be a key driver of several devastating epidemics associated with war and natural disasters. A striking example is Sudan in the 1980s-2000s, where population displacement driven by conflict and famine brought immune-naïve populations into endemic areas, and spread infection into previously unaffected areas. Combined with severe malnutrition and the collapse of health infrastructure, the resulting mortality was catastrophic[13, 40, 41].

⁴Despite sporadic VL cases reported from Pakistan, Bhutan and Sri Lanka, in this thesis ISC refers to India, Nepal and Bangladesh.

The geographic and demographic heterogeneity of VL reflects fundamental differences in host-parasite interactions and immune responses. To understand how these epidemiological patterns arise and why certain groups experience more severe disease, it is necessary to examine the pathophysiology of human *Leishmania* infection.

2.2.2 Pathophysiology

Parasites of the genus *Leishmania* belong to the family *Trypanosomatidae* (class *Kinetoplastea*, phylum *Euglenozoa*) and share many features with two other human pathogens of the same family; *Trypanosoma brucei* — the causative agent of African sleeping sickness (human African Trypanosomiasis), and *Trypanosoma cruzi* — the agent of Chagas disease in the Americas. These vector-borne NTDs are all single-celled protozoa characterized by a flagellum and a kinetoplast — a dense network of mitochondrial DNA giving them a distinctive microscopic appearance.

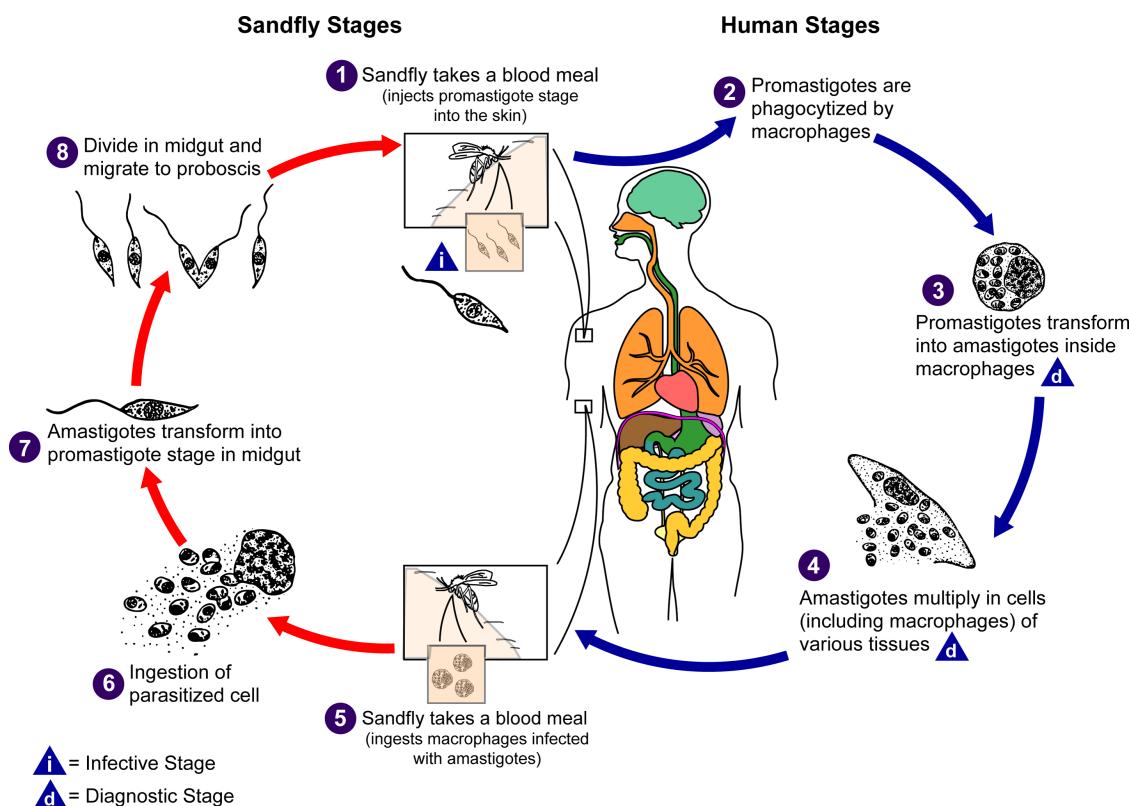


Figure 2.3: Life cycle of the *Leishmania* parasite consists of a vector (sandfly) stage and reservoir (animal) stage. While vector transmission is by far the most common route, it is not essential — direct human-to-human transmission has been reported via needle sharing, organ transplantation, blood transfusion, and mother-to-child transmission. Illustration credit: Centers for Disease Control and Prevention/Alexander J. da Silva/Melanie Moser.

Life Cycle

In the sandfly gut, *Leishmania* parasites exist in their extracellular flagellated promastigote forms. During a blood meal, the parasite is regurgitated into the bite wound and rapidly phagocytosed by macrophages. Intracellularly, in the human host, the protozoa lose their flagellum and transform into amastigotes: oval bodies measuring $\sim 2\text{--}6\mu\text{m}$ in length with their characteristic nucleus and kinetoplast clearly visible on nucleic acid staining. Intracellular amastigotes multiply through binary fission, eventually leading to cell lysis and subsequent uptake by neighboring macrophages to perpetuate infection. In viscerotropic disease caused by *L. donovani* complex, this cycle drives widespread dissemination with macrophage proliferation and granuloma formation across the mononuclear phagocyte system, including in the spleen, liver, bone marrow, and lymph nodes. The cycle completes when sandflies ingest parasitised macrophages during a subsequent blood meal, initiating parasite development within the vector (Figure 2.3).

Immune Evasion

Remarkably, intracellular amastigotes have evolved to survive and replicate within the hostile phagolysosomal environment of the macrophage. Although the full immunological mechanisms remain incompletely understood and beyond the scope of this chapter, key strategies include the presence of a lipophosphoglycan surface coat that protects promastigotes from complement-mediated lysis, and suppression of macrophage activation by inducing functional impairment of cytotoxic T-cell responses. Despite the presence of a pronounced humoral response, with a polyclonal hypergammaglobulinaemia typically seen, the resulting antibodies are predominantly non-neutralising and may even play a role in maintaining the immunosuppressive milieu required for amastigote survival[42, 43]. As the disease progresses, so too does the host's immunosuppressive state, driven by rising levels of immunoregulatory cytokines (especially IL-10 and TGF β) and the destructive remodelling of lymphoid architecture[43, 44].

2.2.3 Clinical Features

The clinical spectrum of *Leishmania* infection is remarkably broad, with asymptomatic carriers outnumbering symptomatic cases by a factor of 5–200 in endemic settings[3, 31, 45]. If symptomatic, disease onset is typically insidious, following an incubation period ranging from several weeks, to months, and occasionally years.

Classic symptoms result from a persistent systemic inflammatory response syndrome with infiltration of the mononuclear phagocyte system, resulting in intermittent fever, weight loss, splenomegaly, often with accompanying hepatomegaly and, in parts of East Africa, lymphadenopathy. The spleen is usually non-tender on palpation, but massive splenomegaly ± hepatomegaly can result in severe abdominal pain. The greyish skin hyperpigmentation ('kala-azar' — literally 'black disease' or 'black fever' in Hindi), described in historical accounts of chronic disease in the ISC before effective therapy became available, is now uncommon[2, 7].

Characteristic laboratory abnormalities include raised inflammatory markers (CRP, ESR), pancytopenia, a polyclonal hypergammaglobulinaemia, and hypoalbuminaemia. Anaemia is often severe, normocytic, and normochromic, and likely multifactorial in origin, with splenic sequestration and anaemia of chronic disease thought to play important roles[46, 47]. Haemoglobin levels at presentation are frequently between 6–10 g/dL[46], resulting in pallor and contributing to weakness.

Without treatment, disease severity correlates with increasing parasite burden[48, 49]. Patients may develop vomiting, diarrhoea, cough, and dyspnoea, reflecting a combination of direct mucosal invasion, and opportunistic infections arising from the host's immunosuppressed state. The presence of oedema, jaundice, severe co-infection, and bleeding with disseminated intravascular coagulation indicates a poor prognosis[50].

2.2.4 Diagnosis

The gold standard for diagnosing VL combines compatible clinical features with direct visualisation of *Leishmania* amastigotes in tissue aspirates obtained from the spleen, bone marrow, or lymph node. Splenic aspiration offers the highest sensitivity (93–99%) but carries a small risk of fatal haemorrhage. Bone marrow and lymph node aspirates are safer but considered less sensitive (~50–80%)[2, 3]. Parasite density is usually expressed using a logarithmic semiquantitative grading system (0–6+) originally described by Chulay and Bryceson (Table 2.1)[51].

Culture of tissue aspirates can improve diagnostic sensitivity but is limited by cost, technical complexity, and a slow turnaround of up to four weeks. Molecular assays have been developed but remain infrequently available outside research settings and regions of high endemicity. Notably, peripheral blood quantitative polymerase chain reaction (qPCR) assays amplifying kinetoplast DNA (kDNA) have shown high sensitivities in patients with both VL and VL/HIV co-infection[52–54], obviating the need for invasive sampling where available. Urine antigen detection has demonstrated specificity but suffers from low diagnostic sensitivity[55, 56].

Table 2.1: Logarithmic grading system for parasite load on microscopy of tissue aspirates described by Chulay and Bryceson in the early 1980s[51]. Smears are stained with Giemsa and examined using a $10\times$ eyepiece and $100\times$ objective lens.

Grade	Average parasite density
0	0 amastigotes/1,000 fields
1+	1–10 amastigotes/1,000 fields
2+	1–10 amastigotes/100 fields
3+	1–10 amastigotes/10 fields
4+	1–10 amastigotes/field
5+	10–100 amastigotes/field
6+	>100 amastigotes/field

A wide gamut of serological (antibody-detecting) tests is available for the diagnosis of VL, including enzyme-linked immunosorbent assays (ELISA), indirect fluorescent antibody (IFA) assays, immunoblots, and rapid diagnostic tests (RDTs)[2]. The rK39 immunochromatographic test (ICT) is the most widely used RDT, providing a binary result within 10–20 minutes from a finger-prick blood sample. In the ISC, rK39 RDTs demonstrate excellent sensitivity (97.0%, 95% CI 90.0–99.5%)[57] and have served as the first-line diagnostic test since the mid-2000s. In East Africa, however, sensitivity is lower (85.3%, 95% CI 74.5–93.2%), and a second serological test — the direct agglutination test (DAT) — is recommended to confirm negative rK39 results[57]. Key limitations of serological tests include their inability to distinguish between active and past infection, with antibodies persisting for months to years following successful treatment and their reduced sensitivity in patients with severe immunosuppression, particularly those with VL/HIV co-infection[3].

2.2.5 Treatment

Injectable pentavalent antimonials have been the workhorse of VL treatment since the 1940s⁵, and despite their relatively toxic adverse effects (pancreatitis, cardiac arrhythmias, hepatitis), they remain first-line therapy in both East Africa (sodium stibogluconate [SSG], as part of combination therapy) and in Brazil (as meglumine antimoniate [MA])[58, 59]. From the early 1980s in Bihar, India, treatment failure rates exceeding 50% were observed with SSG despite dose escalation ($10\rightarrow20$ mg/kg/day) and duration ($6\rightarrow40$ days). Blame was attributed to poor stewardship, with subtherapeutic dosing practices driving resistance[60]. As efficacy declined,

⁵Previously, since the 1910s, tartar emetic was used — a toxic trivalent antimonial compound also used as an emetic.

second-line agents were used — initially pentamidine (limited by severe toxicity), and later amphotericin B deoxycholate (ABD), effective but constrained by infusion reactions, nephrotoxicity, and the need for prolonged hospitalisation.

Over the past two decades, the introduction of three new agents — miltefosine, liposomal amphotericin B (AmBisome®; Gilead Sciences), and paromomycin — has transformed the previously limited and often toxic treatment arsenal[61].

Miltefosine (MF), a repurposed anticancer drug, is the only effective oral agent for VL. Introduced as the first-line treatment in the ISC in 2005, MF played a pivotal role in the early KAE[62–64]. Its use has since declined. Concerns about teratogenicity, gastrointestinal toxicity, and decreasing efficacy[65, 66] led to its replacement in the KAE by single-dose liposomal amphotericin B (LAMB) (AmBisome®; Gilead Sciences) in 2014–15[67]. Outside the ISC, MF performs poorly as monotherapy in East Africa and Brazil[61, 68].

Supported by a WHO–Gilead donation programme, a single intravenous (IV) dose of 10mg/kg LAMB remains the first-line regimen in the ISC owing to its efficacy and safety[69]. At higher cumulative doses of 21–30mg/kg given over 5–10 days, LAMB is also used as first-line therapy in Europe and as a second-line option in Brazil and East Africa, particularly in patients intolerant of pentavalent antimonials (severe disease, extremes of age, pregnancy, renal or hepatic dysfunction, relapse, VL/HIV co-infection).

Paromomycin (PM), an injectable aminoglycoside, is effective both as monotherapy and in combination regimens in the ISC[70]. Despite its low cost and favourable safety profile, uptake in the ISC has been limited. In East Africa, by contrast, SSG–PM combination therapy has been first-line since 2010[58, 71], with evidence also supporting its use alongside MF in both East Africa and the ISC[72, 73].

2.2.6 Elimination Efforts

In areas of anthroponotic transmission, control of VL centres on two interdependent strategies: (i) reduction of the human infection reservoir through early diagnosis and treatment, and (ii) interruption of transmission events through vector control measures. Effective implementation of these approaches requires evidence-based decision-making and sustained political will.

Guided by these principles, in 2005 the governments of Nepal, Bangladesh, and India, with WHO support, signed a Memorandum of Understanding to reduce VL incidence to fewer than 1 case per 10,000 population at the district or sub-district level by 2015. This deadline was later extended and is now embedded within the 2021–2030 WHO NTD roadmap[64, 74–77]. The initial success of the

KAEP was attributed to the introduction of highly sensitive rK39 RDTs, oral MF, and subsequently single dose LAMB, alongside active case detection and vector control measures such as indoor residual spraying (IRS) and insecticide treated nets (ITN)[78]. In October 2023, Bangladesh became the first country to eliminate VL as a public health problem[79]. Nepal and India are currently working to sustain their targets for 3 consecutive years to achieve elimination status[80].

As the ISC enters the consolidation and maintenance phases of the KAEP, concerns regarding sustainability are increasingly voiced[67]. Waning political momentum and financial support threaten the viability of costly IRS and active case detection. Moreover, as the proportion of immunologically naïve individuals increases, so too does the risk of future outbreaks[81].

Buoyed by the KAEP experience, calls for VL elimination in East Africa[82] culminated in the 2023 *Nairobi Declaration*, endorsed by the health ministries of nine endemic East African countries⁶ and aiming to reduce VL incidence by 90% by 2030. Similar to the KAEP, a phased approach has been proposed — consisting of planning, attack, consolidation, and maintenance phases — with emphasis placed on equitable access to diagnosis and treatment, integrated vector management adapted to diverse ecological settings, and strong cross-border collaboration[83, 84].

However, in contrast to the KAEP, the East Africa initiative faces greater operational complexity. Challenges include heterogeneous transmission ecologies, weaker health systems, reliance on multi-dose treatments, and limited access to sensitive diagnostic tools[84].

Early diagnosis and treatment of all human infection reservoirs remains a cornerstone of any successful elimination campaign where transmission is largely anthroponotic. The next section examines the burden, mechanisms, and determinants of VL relapse — a reservoir of particular concern and of critical relevance to elimination.

2.3 Relapse

This section is guided by a systematic review of the literature and presented as a narrative review (see Box 2.2). Search terms were constructed to identify the burden, timing, mechanisms, and determinants of VL relapse, with a focus on immunocompetent patients in the ISC and East Africa. Further details are available in Appendix A.

⁶Chad, Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, Sudan and Uganda

VL relapse is defined as the reappearance of VL signs and symptoms following an initial treatment response[85, 86]. In both research and routine clinical settings, relapse is typically confirmed by direct visualisation of the parasite on a tissue aspirate smear[87].

Relapse can only occur once an initial treatment response is achieved — termed initial cure in clinical efficacy studies. In research settings, this requires both clinical improvement (e.g., defervescence, reduction in spleen size, weight gain, improvement of haemoglobin) and confirmation of parasite clearance by microscopy. This is referred to as *test-of-cure*, and usually occurs within a month of the end of treatment (EoT), although considerable heterogeneity exists in precisely how and when test-of-cure is assessed[88].

Box 2.2: Literature search

Literature search performed from database inception to 11th August 2025 in PubMed (below), Embase and Web of Science. Articles in English were reviewed. Full search details available in Appendix A.

```
("Leishmaniasis, Visceral"[Mesh] OR "visceral leishmaniasis" OR  
"leishmaniasis, visceral" OR "kala azar" OR "kala-azar") AND  
("Recurrence"[Mesh] OR relapse* OR recurrent OR recurrence OR  
recrudescence OR "treatment failure")
```

2.3.1 Burden of Relapse

Reported relapse rates among immunocompetent patients vary widely across studies, reflecting differences in host, treatment, and parasite factors[87]. As a ‘rule of thumb’, relapse rates with current first-line regimens among patients without significant immunosuppression range between 2.5% to 10% (1 in 40 to 1 in 10 patients)[87]. According to a meta-analysis of VL clinical efficacy studies by Chhajed et al., the overall proportion of HIV-negative patients relapsing in the ISC within 6 months of treatment was estimated at 3.5% (95% confidence interval [CI]: 2.8–4.5%) following first-line treatment with single-dose LAMB[87]. Under pragmatic conditions in East Africa, slightly higher 6-month relapse rates of approximately 5% are seen with the first-line combination therapy of PM and SSG[89–91].

These estimates, however, underestimate the true relapse burden: (i) relapses occurring beyond 6-months of follow-up are missed, and (ii) clinical trial populations do not reflect the broader patient population seen in routine care. Chhajed et al. also showed that, across 21 studies reporting both 6 and 12 month relapse

rates, one third of all relapses by 12 months occurred during the second half of the 12 month period[87]. Similarly, several large studies from the ISC have shown comparable or even higher relapses counts occurring between 6–12 months than in the initial 6 month period, prompting calls to extend routine follow-up from 6 to 12 months[65, 92–95]. Furthermore, trials often exclude patients at increased risk of relapse, such as those at the extremes of age, with more severe disease and comorbidities. Trial patients are also managed under controlled conditions that incentivise adherence. These factors collectively bias relapse estimates downward compared with outcomes observed under routine conditions.

2.3.2 Relapse vs. Reinfection

Distinguishing relapse resulting from parasite recrudescence from re-infection with a new strain is important when assessing drug efficacy and relapse determinants. However, unlike malaria[96], VL lacks validated molecular targets for PCR-based confirmation. Nevertheless, accumulating evidence indicates that most relapses result from recrudescence rather than reinfection. For example, Rijal et al. performed kDNA fingerprinting in 8 pairs of bone marrow samples in HIV-negative patients prior to primary infection treatment and at the time of relapse. No evidence of reinfection was found, with 8 distinct kDNA fingerprints identified across the 16 samples that matched at the individual patient level[65]. Similar studies have been performed in VL/HIV co-infection patients in East Africa and Europe employing a variety of molecular techniques, and showing that while reinfection does occur, it is considerably less common than recrudescence[97–100].

2.3.3 Relapse Determinants

When selecting candidate predictors for inclusion in a prognostic model, it is important to draw on previously described predictors[101]. To provide important context for the subsequent chapters on relapse model development, this section summarises the determinants of relapse identified through the literature review.

For immunocompetent patients, the review aims to be exhaustive. Studies were excluded if they (i) did not adopt a longitudinal design in which index VL cases were linked to subsequent relapse episodes in the same patients, (ii) included more than 5% VL/HIV co-infection without reporting relapse predictors separately by HIV status; or (iii) focused solely on treatment regimens and/or biomarkers (including molecular targets or cytokines) that are not routinely measured in clinical practice. Although not intended to be comprehensive, key studies conducted in patients

with VL/HIV co-infection, as well as those reviewing biomarkers or treatments predictive of relapse, are also discussed.

Four systematic reviews describing predictors of relapse were identified: two including patients with and without VL/HIV co-infection[102, 103] and two focussing specifically on patients with VL/HIV co-infection [104, 105]. Where appropriate, references from these reviews inform the narrative synthesis.

It is important to recognise that whether a study identifies a significant association between a predictor and relapse does not necessarily correspond to whether or not the predictor is important. For example, (i) not all predictors are considered by all studies, (ii) many studies have small sample sizes and are therefore underpowered to detect certain associations, and (iii) a wide range of study designs, statistical tests, predictor transformations, and modelling strategies are employed, affecting what is considered ‘significant’. Furthermore, the significance of an association will also depend on the other variables adjusted for in the prediction model.

Immunocompetent Patients

A total of 11 studies reporting relapse determinants in immunocompetent patients were identified, and are presented in Table 2.2. Eight studies were conducted in the ISC, including India[92, 94, 95, 106, 107], Bangladesh[28, 108], and Nepal[65], two in East Africa, including South Sudan[109] and Kenya[110], and one in Georgia[111]. The median study size was 1,143 patients (range 115[65] to 8,537[94]). Two studies presented outcomes from the same trial[95, 106], although they are reported separately here due to differences in sample size and methodology. Follow-up ranged from 6 months to 4 years, and relapse proportions from 2.6%[108] to 20.8%[65]. Further details, including study design and methodologies, are provided in the [Supplementary Material](#).

Age, treated categorically (≥ 2 levels), was the most frequently reported relapse determinant. All 11 studies considered age as a candidate predictor, with eight demonstrating statistically significant ($p < 0.05$) or borderline significant ($0.05 \leq p < 0.1$) associations in unadjusted models[65, 92, 94, 95, 106–108, 111]. When adjusted models were considered, age remained significant in all but one study[92]. Two ISC studies that modelled ≥ 3 age categories showed a U-shaped relationship, with increased relapse risk in young children (< 5 years) and older adults (≥ 40 or ≥ 45 years)[94, 108]. Other studies identified increased risk only in younger groups; < 12 or < 15 years in the ISC[65, 92, 95, 106] and < 1 year in Georgia[111]. Notably, the two East African studies did not identify age as a significant predictor[109, 110], although this may reflect limited power (17 relapses

in Kennedy et al.[110]), or selection bias due to incomplete linking of relapse and index cases[109]. No study explicitly modelled age as a continuous variable.

Spleen size was the next most frequently identified determinant, considered in seven studies. Five reported significant associations in unadjusted analyses, and four in adjusted models[92, 94, 108, 109, 111]. Definitions and timing varied. Lucero et al. reported that larger spleens at discharge predicted relapse (OR 1.27, 95% CI 1.10–1.47 per cm below the costal margin). Sundar et al. found approximately twice the odds of relapse in patients with admission spleen size >4 cm[92]. Gorski et al. identified increased relapse odds with larger spleens at discharge *and* admission, when measured with Hackett grade[109]. Kajaia et al. reported increased relapse risk with larger spleens at admission when measured by the Kandelaki splenometric method[111, 112]. Instead of absolute spleen size, Burza et al. modelled change in spleen size during admission: patients with a reduction ≤ 0.5 cm/day had 1.7-fold higher odds of relapse (95% CI 1.1–2.5) compared with those with greater reductions[94].

Symptom duration prior to treatment was considered in six studies, with four identifying significant associations in both unadjusted and adjusted models[94, 95, 106, 111]. In the ISC, Burza et al. reported that patients with ≤ 4 weeks of symptoms had higher relapse odds (1.6-fold vs 4–8 weeks; 2.3-fold vs >8 weeks), with similar effects after adjusting for age, sex, and change in spleen size[94]. Goyal et al. found that ≤ 8 weeks of symptoms was associated with 3.3-fold (95% CI 1.3–8.4) higher relapse odds[95] and a 3.6-fold (95% CI 1.4–9.1) higher relapse hazard in time-to-event analysis[106]. In contrast, Kajaia et al. reported that ≥ 90 days of symptoms was associated with higher relapse risk in Georgia (OR 3.9; 95% CI 1.8–8.5) after adjusting for haemoglobin and age[111]. Kennedy et al. included symptom duration but did not identify a significant association, perhaps due to low statistical power[110].

Although sex was considered in all studies, only three ISC studies found significant associations with relapse[92, 94, 107]. Each reported an approximate doubling in relapse odds[92, 94] or rates[107], with similar effect sizes seen in adjusted analyses.

Admission haemoglobin (Hb) was included in eight studies[65, 92, 94, 95, 108, 110, 111] and was significant in three[108, 110, 111]. Lucero et al. observed strong associations between lower Hb and relapse in partially adjusted models, although these were not retained in the fully adjusted model (OR 1.40, 95% CI 1.09–1.72 and 1.45, 95% CI 1.15–1.85, per g/dL decrease, for admission and discharge Hb, respectively). Kajaia et al. reported a strong association, with relapse 12-fold

(95%CI 4.1–34.8) more likely in patients with Hb <60 g/L vs \geq 80 g/L, persisting after adjustment for age and symptom duration.

Markers of malnutrition were inconsistently defined across studies, and reporting was often unclear. Gorski et al. and Burza et al. used age-specific definitions combining BMI, BMI-for-age z-scores, and weight-for-height z-scores[94, 109]. Lucero et al. used a similar approach, combining weight-for-height z-scores and BMI[108]. Goyal et al. and Kennedy et al. described ‘severe wasting’ and ‘malnutrition’, respectively, without further definitions[95, 110]. Rijal et al. and Sundar et al. relied on single indicators (BMI and weight, respectively)[65, 92]. Only Sundar et al. observed a significant association, with patients \leq 30 kg at higher risk, although the causal interpretation is likely confounded by age, given that the study recruited participants of all ages[92].

Table 2.2: Summary of studies predictors of VL relapse in immunocompetent patients. Excluding: studies only looking at treatment regimen or biomarkers. BPKIHS: B.P. Koirala Institute of Health Sciences; ISC: Indian subcontinent; KAMRC: Kala-azar Medical Research Centre; MA: meglumine antimoniate; MSF: Médecins Sans Frontières; Hb: haemoglobin; LAMB: liposomal amphotericin B; MF: miltefosine; PM: paromomycin; RBC: red blood cell; SDA: single dose liposomal amphotericin B 10mg/kg; SSG: sodium stibogluconate; VL: visceral leishmaniasis; wks: weeks; yrs: years.

Study	Location	Treatment	n (relapse) %	Significant predictors — unadjusted model ¹	Significant predictors – adjusted model ²
ISC					
Burza 2014[94]	MSF clinics, Bihar, India	20mg/kg LAMB (4 x 5mg/kg)	8,537 (119) 13.9%	age <5****, age ≥ 45** vs. 15–30 yrs; male sex***; other backwards caste* vs. general category; symptom duration ³ > 8 wks***, > 4 to ≤8wks** vs. ≤4 wks; spleen size change ≤0.5cm/day vs. >0.5cm/day	age <5****, age ≥45** vs. 15–30 yrs; male sex***; symptom duration ³ >8 wks**, >4 to ≤8wks** vs. ≤4 wks; spleen size change ≤0.5cm/day vs. >0.5cm/day
Goyal 2019[95]	Public health facilities, Bihar, India	SDA; LAMB+MF; MF+PM	1,353 (75) 5.5%	age 2–12 yrs** vs. >12 yrs; symptom duration ≤8 wks*** vs. >8 wks; treatment****	age 2–12 yrs [†] vs. >12 yrs; symptom duration ≤8 wks [†] vs. >8 wks; treatment MF+PM [†] vs. SDA
Goyal 2020[106]	[as above]	[as above]	1,750 (79) 4.5%	age 2–12 yrs ^{††} vs. >12 yrs; treatment with MF+PM ^{††}	age 2–12 yrs*** vs >12 yrs; symptom duration ≤8 wks*** vs. >8 wks; treatment MF+PM**** vs. SDA
Lucero 2015[108]	MSF clinic, Fulbaria, Bangladesh	15mg/kg LAMB (3 x 4mg/kg)	1,521 (39) 2.6%	age <5 yrs***, age ≥40 yrs** vs. 18–39 yrs; lower admission Hb***; lower discharge Hb***; larger discharge spleen size***	age <5 yrs***, age ≥40 yrs** vs. 18–39 yrs; larger discharge spleen size**
Mondal 2019[28]	Hospital in Mymensingh, Bangladesh.	8 different regimens	984 (69) 7.0%.	treatments compared only: MD-LAMB*, MF**, LAMB+PM**, LAMB+MF***, SDA****, PM****, MF+PM**** vs. SSG	treatment: MD-LAMB*, MF**, LAMB+PM**, SDA***, LAMB+MF****, PM****, MF+PM**** vs. SSG
Rijal 2013[65]	BPKIHS, Eastern Nepal	MF	115 (24) 20.9%	age ≤12 yrs** vs. >12 yrs	[not performed]
Sundar 2019[92]	KAMRC, Bihar, India	SDA	1,143 (66) 5.8%	age ≤15 yrs* vs. >15 yrs; male sex**; weight ≤ 30kg** vs. >30kg; spleen size >4cm*** vs. ≤4cm	male sex***; weight ≤ 30kg** vs. >30kg; spleen size >4cm*** vs. ≤4cm

continued on next page

Table 2.2: continued

Study	Location	Treatment	n (relapse) %	Significant predictors — unadjusted model ¹	Significant predictors – adjusted model ²
East Africa					
Gorski 2010[109]	MSF clinics, South Sudan	SSG, SSG/PM, LAMB	8,090 (166) ⁴	treatment centre: Lankien **** vs other; admission spleen size ^{5***} ; discharge spleen size ^{***} ; treatment ^{****} ; lower % gain in body weight [*]	admission spleen size ^{5†, 2†, ≥3†} vs 0; discharge spleen size ^{2†, ≥3†} vs 0; treatment SSG/PM [†] vs SSG
Europe					
Kajaia 2011[111]	Institute of Parasitology and Tropical Medicine, Tbilisi, Georgia	MA	300 (21) 7.0%	age ^{**} : higher risk in <1 yrs; symptom duration ^{***} : higher risk with longer duration; Hb ^{****} : higher risk with Hb <60g/l; RBC [*] : higher risk $<2.0 \times 10^{12}/l$; lymphocytes ^{**} : higher risk with $\geq 80\%$; admission spleen size ^{**} : higher risk with larger spleens	age <1 yr ^{**} vs. >1 yr; symptom duration ≥ 90 days ^{***} vs <90 days; Hb <60g/l ^{****} vs. Hb <60g/l

¹ Significant predictors in Lucero et al. are in fact adjusted for sex and age. Kajaia et al present the overall p-value across all predictor categories and 95% CIs for each category. Overall p-values are presented, and the trend commented on.

² 3 studies adjusted the multivariable model for other non-significant variables, including Lucero et al. (sex, admission and discharge haemoglobin, admission spleen size), Mondal et al. (sex, age, treatment, and various others), Gorski et al. (age, sex, calendar year, treatment centre)

³ Shorter symptom duration associated with higher relapse risk in Burza 2014.

⁴ 166 relapses cases could be matched with primary case records, and does not reflect total relapse number.

⁵ Spleen size recorded as Hackett grade in Gorski 2010.

* $0.05 \leq p < 0.1$.

** $0.01 \leq p < 0.05$;

*** $0.001 \leq p < 0.01$

**** $p < 0.001$.

[†] $p < 0.05$ (inferred as confidence interval does not cover null).

^{††} Significance level not stated.

VL/HIV Co-infection

Relapse rates in patients with VL/HIV co-infection often exceed 20–50%[104, 113, 114], highlighting the importance of host immunity in achieving lasting cure.

Two systematic reviews were identified that summarised relapse determinants in this immunosuppressed population, drawing on 18 studies (Cota et al., 2011)[104] and 15 studies (Alemayehu et al., 2016)[105], respectively. Significant predictors of relapse included low baseline CD4⁺ T-cell counts (particularly <100 cells/ μ L), previous history of VL relapse, lack of improvement in CD4⁺ counts during follow-up, absence of secondary prophylaxis, and the timing of highly active antiretroviral therapy (HAART) initiation.

Since the publication of these reviews, several important studies have shed further light on relapse determinants in VL/HIV co-infected patients[113, 115, 116]. In 2017, Abongomera et al. reported outcomes from a retrospective study of 146 co-infected patients treated at an MSF-supported clinic in Northwest Ethiopia between 2008 and 2013, in which 44 (30.1%) relapsed during follow-up. In addition to the timing of HAART initiation, further predictors included high baseline tissue parasite load (adjusted hazard ratio [aHR] 6.63, 95% CI 2.64–16.63, 6+ vs \leq 6+) and the presence of splenomegaly on admission (borderline significant in unadjusted analysis)[115].

More recently, Costa et al. (2023) published a prospective study of 169 co-infected patients from Maranhão, Brazil (2013–2020), in which 70 (41.1%) relapsed during 12 months of follow-up. Baseline splenomegaly, lymphadenopathy, previous VL relapse, HAART regimen, HAART duration, elevated creatinine, and elevated urea were all statistically significant predictors of relapse in unadjusted analyses[116].

In contrast to findings in immunocompetent patients, only one study identified age as a statistically significant predictor of relapse. Burza et al. demonstrated an approximate doubling of relapse hazard among patients \geq 40 years, using routinely collected data from MSF treatment centres in Bihar, India (2007–2012)[114].

Treatments

After VL/HIV co-infection, treatment is arguably the second most important predictor of relapse. This is evident across numerous studies, where the most common reason for failing to achieve the primary outcome of definitive cure — defined as initial cure and relapse-free survival for 6 months — is relapse[61, 71, 72, 92, 106]. Summarising outcomes from all VL efficacy studies is beyond the scope of this thesis, although several observations merit discussion.

Firstly, as summarised by Chhajed et al., although relapse risk varies considerably across regimens, combination therapies are generally associated with lower relapse

risk than monotherapies[87]. After adjusting for age and symptom duration, Goyal et al. showed that in India, treatment with paromomycin and miltefosine combination therapy was associated with significantly reduced odds of relapse compared with single-dose LAMB 10 mg/kg (aOR 0.21, 95% CI 0.08–0.55). Similarly, in a large cohort study from Bangladesh, Mondal et al. found that, with the exception of SSG and multiple-dose LAMB, combination regimens were associated with lower relapse rates compared with paromomycin and miltefosine monotherapies[28]. A possible exception to this pattern is SSG/PM combination therapy. Using programmatic MSF data from South Sudan, 1999–2007, Gorski et al. demonstrated an approximate doubling of relapse odds in the SSG/PM group compared to SSG monotherapy (OR 2.08, 95% CI 1.21–3.58)[109].

Secondly, drug dose and treatment duration are also important predictors of treatment failure and relapse. Chhajed et al. showed this at the aggregate level by performing a meta-regression of relapse risk in the ISC against the dose of single-dose LAMB, demonstrating that higher LAMB doses were associated with lower relapse risk (OR 0.81 per 1 mg/kg increase, 95% CI 0.72–0.91)[87]. Similar relationships between dose and overall treatment failure (lack of initial cure or subsequent relapse) have been demonstrated under trial conditions for both LAMB[117] and paromomycin[118, 119]. In East Africa, Dorlo et al. used a paediatric pharmacokinetic–pharmacodynamic (PK–PD) model to show an inverse relationship between miltefosine exposure and relapse hazard, with similar findings reported in the ISC[120]. These results supported the development of allometric dosing strategies for paediatric miltefosine[121, 122].

Lastly, both the intrinsic infectivity of the parasite strain and the development of drug resistance contribute to increasing rates of initial treatment failure and, when initial cure is achieved, subsequent relapse. A well-known example is the emergence of antimony resistance in Bihar, India, where treatment failure and relapse rates following treatment with SSG increased from <5% to >50% during the 1980s and 1990s, despite incremental escalation in SSG dose and duration[60, 123]. These failures have been attributed to both antimony resistance[124], and also to the selective survival and transmission of more infectious parasite strains[125]. Similar concerns arose following the widespread introduction of miltefosine in the ISC in the late 2000s, when increasing relapse rates were observed[65, 66, 126]. Interestingly, comparisons of relapsing versus non-relapsing strains revealed no evidence of drug resistance, although relapsing strains were found to be more infectious[127]. More recently, Naylor-Leyland et al. reported increasing relapse rates between 2001 and 2018 that could not be explained by patient-level factors, prompting concerns about declining SSG/PM efficacy potentially due to emerging resistance[128].

Biomarkers

Since tissue aspirate sampling is invasive, substantial effort has been directed toward developing biomarkers that can serve both as a test-of-cure following treatment and as a diagnostic test of relapse[86]. In fact, a 2015 systematic review identified 53 biomarkers from 170 studies with potential to be used for monitoring post-treatment outcomes in Leishmaniasis[129]. Biomarkers can be broadly categorised into two categories: (1) direct markers of parasite burden, including DNA and antigen detection; and (2) indirect markers of host immunity, such as antibodies, cytokines and acute-phase proteins.

A large portion of the VL biomarker literature focuses on the direct detection of *Leishmania* DNA/RNA in both immunosuppressed[130–135] and immunocompetent patients[54, 136–139]. In particular, real-time quantitative PCR (qPCR) targeting kDNA, performed on the buffy coat of peripheral blood, has been confirmed as a strong predictor of relapse[54, 136, 138, 139], although routine use is limited by the need for specialised laboratory expertise and high costs. In a landmark 2021 study, Verrest et al. used qPCR measurements from 177 immunocompetent patients enrolled in DNDi trials in East Africa⁷ and demonstrated that qPCR levels measured between treatment initiation and day 56 significantly predicted relapse, with areas under the receiver operating curve (AUC) of 0.71, 0.74, and 0.92 on days 14, 28, and 56, respectively[139]. Using the same qPCR data, Verrest et al. (2024) developed a semi-mechanistic population PK–PD model describing parasite replication, drug action, and post-treatment parasite clearance. The model successfully predicted relapse based on modelled day 28 and 56 parasite loads and provided the first direct evidence that relapse risk depends not only on initial parasite clearance but also on subsequent host immune responses[54]. Interestingly, inclusion of haematological and biochemical parameters,⁸ however, did not account for variation in post-treatment qPCR values.

Beyond molecular testing, several studies have shown an association between relapse and the degree of *Leishmania* antigenuria in patients with VL/HIV co-infection[55, 56]. In Ethiopian patients, higher levels of urinary antigen at test-of-cure were strongly associated with relapse over the following 12 months (HR 9.8, 95% CI 1.8–82.1, comparing 1–10 parasites/10 fields with no parasites detected using the KATex assay).

⁷LEAP 0714 (30 children treated with allometric miltefosine), LEAP 0208 (151 patients receiving miltefosine plus LAMB combination regimens), FEXI VL 001 (14 patients receiving fexinidazole)

⁸including Hb, white blood cells (WBC), platelets, and creatinine

Post-treatment IgG subclass titres have also been linked to relapse in both immunocompetent and immunosuppressed individuals[140–143]. However, because of the long half-life of immunoglobulins, their ability to predict relapse at the time of initial cure assessment remains uncertain. In asymptomatic patients, however, serological studies have shown that individuals with higher antibody titres are more likely to progress to symptomatic disease[144, 145].

A variety of non-serological and indirect biomarker panels have been evaluated for assessing disease activity during asymptomatic infection, active disease, and post-treatment recovery[146–151]. In East African patients, Kip et al. reported that the change in neopterin, a marker of macrophage activation, between EoT and day 60 of follow-up was predictive of relapse, with an AUC of 0.84. In a subsequent study of 34 Ethiopian VL/HIV co-infected patients, half of whom relapsed, Takele et al. showed that relapse was associated with (i) failure to restore antigen-specific IFN γ production, (ii) persistently low CD4 $^{+}$ T-cell counts, and (iii) high T-cell expression of PD1. These results underscore the importance of effective cell-mediated immunity in achieving sustained cure.

Summary of Relapse Determinants

A substantial and rapidly growing evidence base has been identified describing the determinants of VL relapse, although methodological heterogeneity complicates synthesis.

Among immunocompetent patients — the focus of this thesis — the most consistently identified predictors are clear. Extremes of age (young children and older adults), larger spleen size, whether measured at admission or at EoT, male sex, and the severity of anaemia (at admission and EoT) are repeatedly associated with higher relapse risk. In contrast, evidence for malnutrition is weak, perhaps in part due to the varying definitions, and nuances in how measures are adjusted for age. Symptom duration shows conflicting associations. Shorter pre-treatment symptom intervals were strongly linked to higher relapse risk in two ISC studies, yet an opposite association was reported in the study from Georgia — highlighting potential contextual or methodological modifiers.

In patients with VL/HIV co-infection, predictors align more with immunological plausibility: markers of profound immunosuppression (notably low baseline CD4 $^{+}$ counts) and indicators of inadequate immune reconstitution (including timing and duration of HAART, absence of secondary prophylaxis) were the dominant determinants of relapse identified.

As anticipated, treatment-related factors are also highly influential. Treatment regimen, dose, and duration modify both initial cure and subsequent relapse risk, and therefore any prognostic model should be accounting for treatment variables where possible.

Finally, biomarker research (particularly peripheral blood qPCR) shows promising predictive performance, but current approaches are constrained by cost, laboratory requirements and limited routine availability, restricting their immediate applicability in many endemic settings.

2.4 Summary

VL remains a highly neglected tropical disease, disproportionately affecting the poorest and most marginalised communities. Despite substantial gains over the last two decades — most notably in the ISC, where coordinated elimination efforts have driven steep reductions in incidence — VL continues to impose a considerable clinical and economic burden. Sustaining these achievements is challenging, and translating success to high-burden regions such as East Africa remains an urgent global health priority[76].

Relapse is a critical, yet often understated, component of this challenge, with consequences both at the individual patient level and for public health more broadly.

For the patient, relapse is associated with heightened morbidity and mortality, exposure to prolonged and often toxic second-line therapies, and considerable direct and indirect financial costs for already vulnerable households.

From a public health and elimination perspective, relapse carries further implications. In anthroponotic transmission settings, early identification and effective treatment of relapse cases are essential to interrupt transmission. Moreover, parasite strains isolated from relapse cases can harbour resistance mutations and demonstrate greater fitness, underscoring their potential role as a consequential parasite reservoir.

Given the clinical, economic, and epidemiological significance of relapse, there is a clear and globally recognised need to improve the identification of individuals at greatest risk[84, 86]. Motivated by this, the overarching aim of this thesis is to determine whether clinical trial data contained within the IDDO VL data platform can be leveraged to support the risk stratification of patients who are likely to progress to relapse following initial cure. In particular, this thesis explores whether such data can inform the development of a robust prognostic model for relapse.

If a prognostic model for VL relapse already exists, data from the IDDO VL data platform could be used to validate and, where necessary, update the model[101].

Therefore, to establish the current evidence base, the next chapter presents a systematic review of prognostic models developed for VL, encompassing both relapse-specific models and those predicting broader clinical outcomes.

3

Prognostic Models Predicting Clinical Outcomes in Patients Diagnosed with Visceral Leishmaniasis: A Systematic Review

4

Methodology

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4.1 Introduction

As outlined in Chapter 2, VL relapse is consequential not only for individual patients but also poses a threat to sustained elimination efforts. Accordingly, the development of a non-invasive tool to predict relapse — functioning as a ‘test-of-cure’ following initial treatment — has been identified by the WHO as a research priority[84, 86, 152]. A prognostic model represents a potential solution: by

quantifying the relationship between patient characteristics and subsequent relapse events, relapse risk in future patients can be estimated and clinical decision-making informed. However, as demonstrated in Chapter 3, no prognostic models for VL relapse have been published to date.

To address this evidence gap, four prognostic models are developed using IPD from the IDDO VL data platform: two for patients from the ISC and two for patients from East Africa. Within each region, one model includes parasite grade at baseline (pre-treatment) assessment, and one model excludes parasite grade, reflecting differences in data availability and clinical practice. All models use routinely collected information available at the time of initial cure assessment to predict six-month relapse among VL patients without HIV co-infection.

The development and evaluation of clinical prediction models is supported by an extensive and growing methodological literature. Over the past decade, reporting guidelines for prediction model studies have been established[101, 153–155], alongside an increasing number of reviews and recommendations that define best practice[156–160]. In particular, the application of meta-analysis techniques to IPD from multiple studies presents exciting new opportunities for prediction model development and evaluation[155, 161]. Notable opportunities include increased sample sizes leading to greater statistical power, and the ability to explore heterogeneity in predictor effects and model performance across different settings. Additionally, IPD can be used to standardise inclusion criteria and outcome/predictor definitions across included studies. However, as we lay out in this chapter, the use of IPD in prediction model research also introduces challenges; specifically (i) the need for statistical models that account for clustering of participants within studies and (ii) the presence of missing data, which can be sporadically missing within studies, or entirely missing from one or more studies[155].

The aim of this chapter is to describe and justify the methodology used for model development and evaluation — from data acquisition to final model presentation. Guidelines and methodological texts are cited accordingly, and checklists provided for current reporting guidelines on prediction model studies (TRIPOD-AI and TRIPOD-Cluster)[101, 155]. Additional material is presented in Appendix B and in the Supplementary Material.¹ A protocol is available on the Open Science Framework.²

This chapter’s structure closely mirrors the methodological workflow as outlined in Figure 4.1, with sections on data harmonisation, model development, and internal validation. In keeping with best practice, and similar to the approach

¹Available at <https://github.com/jpwil/dphil>.

²Created Nov 8, 2024, available at <https://osf.io/z4bdn>.

adopted in Chapter 3, the research question is presented in Box 4.1 using the PICOTS (population, index model, comparator model, outcome, timing, and setting) framework[161, 162]. Further elaboration of the eligibility criteria, and standardised definitions of predictors and the outcome are considered in the following section.

All analyses were performed using R version 4.4.1[163], with R packages cited in the relevant sections below. R scripts used for model development and evaluation are provided in the [Supplementary Material](#).

Box 4.1: Definition of the research question: a PICOTS approach

Population HIV-negative patients that are prospectively recruited into a clinical trial with a diagnosis of visceral leishmaniasis, confirmed either serologically or parasitologically. No restrictions are placed on age, sex or treatment regimen.

Index models For each setting, two prognostic models are developed; one including baseline parasite grade from a tissue aspirate, and one without. The models predict the *future* occurrence of relapse, using patient information collected at treatment baseline. The intended time of model use is following a successful assessment of treatment response.

Comparator model As established in Chapter 3, no published relapse models are available for comparison or updating.

Outcome Relapse is defined as the recurrence of signs and symptoms of VL requiring rescue treatment, and following demonstration of an initial treatment response.

Timing Relapse occurring within 6-months of test-of-cure (typically occurring at the time of treatment completion, or within 30 days of starting treatment).

Setting Participants from either the Indian subcontinent or East Africa.

4.2 Data Harmonisation

Here, data harmonisation refers to the process of data acquisition, curation, and any subsequent data manipulation required to produce a single analysis dataset ready for model development.

In the interest of full disclosure, data acquisition was completed by IDDO colleagues prior to the commencement of this DPhil project. The first stage of data curation — conversion of the contributed datasets to the Clinical Data Interchange Standards Consortium (CDISC) Study Data Tabulation Model (SDTM) standard — was performed by the IDDO data engineering team with support from the IDDO science team (myself included). Subsequent methodological steps were led by myself.

4.2.1 Data Acquisition

A systematic review of the scientific literature was first performed in 2016, with the aim of comprehensively cataloguing all existing VL clinical trials (PROSPERO: CRD42021284622)[164]. 145 trials were initially identified (1980–2016, n = 26,986 patients), with further trials added during periodic updates according to an open protocol[165]. Between 2018–2022, corresponding authors of the identified VL clinical trials were invited to share their IPD with the IDDO VL data platform, in line with the General Data Protection Regulation (GDPR)-compliant IDDO data sharing policy[166, 167].

4.2.2 Data Curation

Conversion of the contributed datasets to an analysis-ready dataset of all eligible IPD occurred in two key stages.

Stage 1: CDISC SDTM Curation

To facilitate reusability and interoperability, contributed datasets were standardised to a common storage format: the CDISC-compliant SDTM standard[168], adapted by IDDO for VL[169]. During this process, contributed datasets underwent *pseudonymisation*,³ prior to being available for data sharing requests. Briefly, SDTM format datasets comprise a number of standardised domains (tables) containing related information (e.g. patient demographics, laboratory results, treatment administration, clinical signs and symptoms). Each domain contains a set of standard variables (table columns, e.g. STUDYID, USUBJID, VISITDY) alongside VL-specific variables defined by IDDO (e.g. parasite grade, spleen size). Further details of the curation process are available in the [IDDO SDTM Implementation Guide](#).⁴

³ ‘...processing of personal data in such a manner that the personal data can no longer be attributed to a specific data subject without the use of additional information’ <https://ico.org.uk/for-organisations/uk-gdpr-guidance-and-resources/data-sharing/anonymisation/pseudonymisation/> (accessed 15 Dec 2025).

⁴ Available at <https://www.iddo.org/tools-and-resources/data-tools>, free registration required.

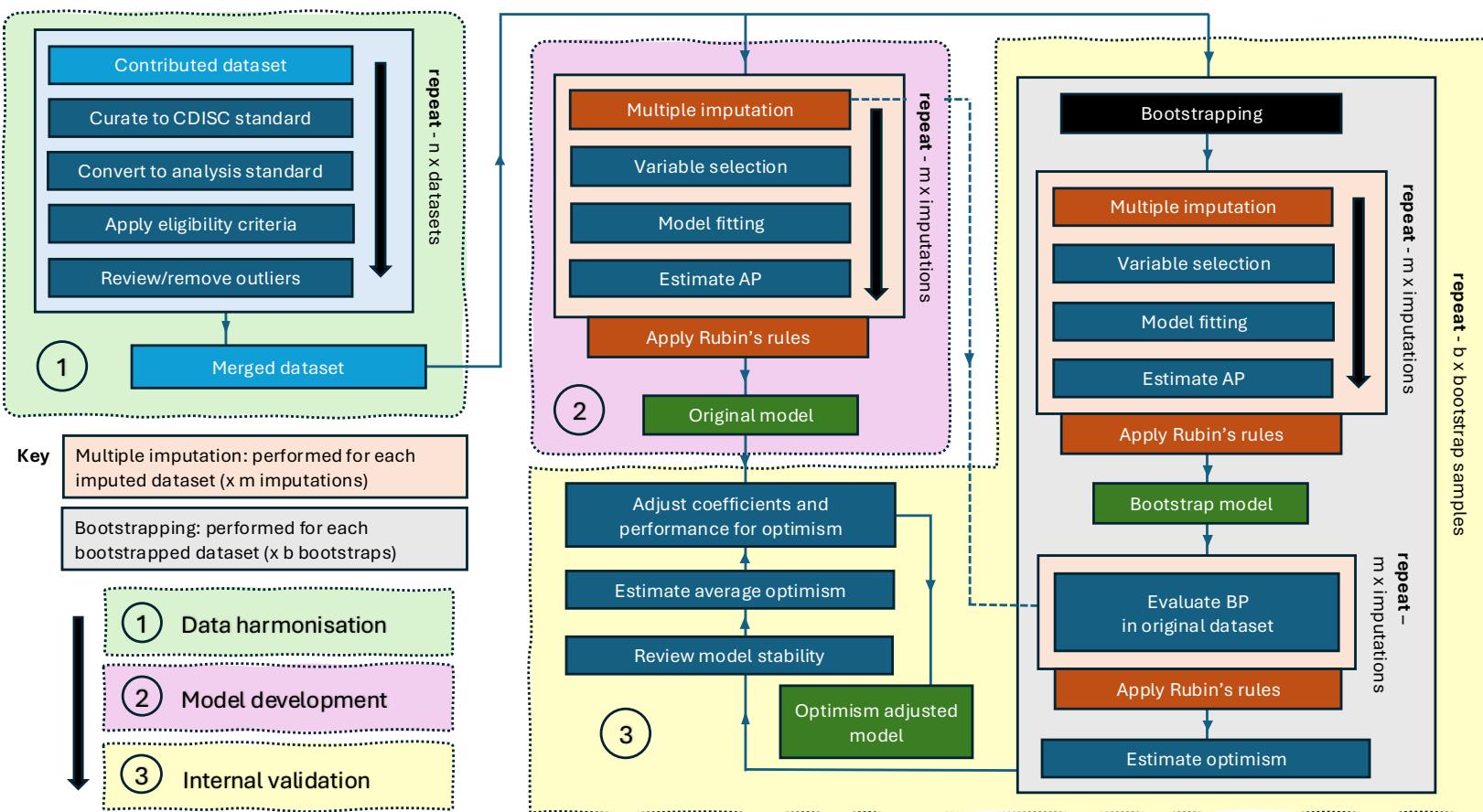


Figure 4.1: Schema of methodological workflow. ① Data harmonisation is performed for each contributed dataset including: initial curation (by the IDDO data engineering team) to the CDISC SDTM format, application of inclusion and exclusion criteria, and removal of outliers. Curated and cleaned datasets are converted into an analysis (wide) format and merged prior to ② model development. Multiple imputation is used to create ($m = 30$) imputed (complete) datasets. Variable selection, model fitting, and apparent performance evaluation is performed on all imputed datasets. Estimates are pooled using Rubin's Rules. Bootstrapping is used to perform ③ internal validation, allowing (i) review of model stability and (ii) optimism adjustment of performance measures and original model coefficients. All model development steps, including multiple imputation, are repeated for each of the ($b = 500$) bootstrap datasets. The resulting bootstrap models ($b = 500$) are evaluated both in the corresponding bootstrap (imputed) datasets and the original (imputed) datasets, and pooled using Rubin's Rules. The mean of the differences of the pooled performance measures (in bootstrap vs. original dataset) are used to shrink the original model coefficients and apparent performance measures, resulting in the final optimism-adjusted model. AP: apparent performance; b: number of bootstraps; BP: bootstrap model performance; CDISC: Clinical Data Interchange Standards Consortium; IDDO: infectious diseases data observatory; m: number of imputations; n: number of contributed studies. SDTM: Study Data Tabulation Model.

Stage 2: Analysis–Ready Dataset Curation

Subsequently, SDTM format datasets were converted to a single analysis–ready dataset, primed for model development. This stage consisted of multiple steps, refined iteratively over several months and in close consultation with the IDDO data engineering team:

- Identification and removal of spurious data points (e.g. outliers, discussed below)
- Application of study and participant eligibility criteria (Section 4.2.3)
- Creation of a standardised outcome variable according to a pre-defined definition (Section 4.2.4)
- Conversion of the datasets from a long to wide format, consisting of one row per participant
- Merging of all datasets into a single analysis dataset

Data wrangling during the second curation stage was performed with the `tidyverse` suite of R packages[170]. Identification and removal of spurious data points was performed through subgroup tabulations and visual inspection of histograms and scatter plots. Where two incongruous data points were identified, for example, incompatible height and weight values, a third variable, such as BMI or age, would be used to identify the spurious value. Data points considered to be outliers were converted to missing values. A complete record of all data cleaning steps, including outlier identification and removal, was maintained and documented in commented R scripts.

In Section 2.3 of Chapter 2, relapse was defined broadly as ‘the reappearance of VL signs and symptoms following an initial treatment response’, and ‘typically confirmed by direct visualisation of the parasite on a tissue aspirate smear’. Despite appearing a clear definition, on closer inspection it can be appreciated that even subtle variations in eligibility criteria, study design, and the definition of efficacy endpoints can, at times unexpectedly, impact the proportion of patients experiencing relapse as a study outcome.

4.2.3 Population at Risk

Clear specification of the population at risk is fundamental to understanding the model’s real-world applicability[101, 161]. Particular attention is given to the definition of initial cure, since (i) relapse can only occur following an initial

Box 4.2: Eligibility criteria

- **Study-level inclusion criteria**
 - Studies conducted in either the ISC (India, Nepal, Bangladesh) or East Africa (Ethiopia, Sudan, South Sudan, Kenya, Uganda)
 - Prospective design, defined as participants having provided informed consent
 - Participants recruited with a diagnosis of VL as defined by a combination of clinical symptoms and either parasitological or serological confirmation
 - Studies that report, as a minimum, the treatment regimen including at least the drug name(s), dose and duration
 - Recruited a minimum of 6 patients
 - Included a minimum of 6 months of prospective follow-up from treatment initiation
 - Reported VL relapse events during the 6-month follow-up period
- **Participant-level exclusion criteria**
 - Participants with HIV co-infection or from a setting with high HIV co-infection prevalence and without a negative HIV test
 - Participants who were confirmed pregnant at the time of treatment initiation
 - Participants with symptomatic treatment failure requiring rescue treatment, identified either before or at initial cure assessment

treatment response, and (ii) heterogeneity in study-level cure definitions can be partly addressed through IPD-based standardisation.

Inclusion and exclusion criteria were applied at the study and participant levels and are presented in Box 4.2. Criteria are chosen according to (i) the eligibility criteria applied in the original systematic review from which identified study authors were invited to contribute their IPD[164], (ii) the range of studies available in the IDDO VL data platform, and (iii) the resulting impact and applicability of models developed.

Study-Level Criteria

Study-level inclusion criteria were applied to ensure that contributed studies were sufficiently comparable in terms of epidemiological context, study design, and outcome ascertainment to permit meaningful harmonisation and pooled analysis.

Studies were limited to those conducted in East Africa and the ISC, reflecting both the public health relevance of relapse prediction in regions with ongoing VL

elimination programmes, and the availability of IPD the IDDO VL data platform. On review of the IDDO inventory[171], only two studies were conducted outside these regions — one in Greece conducted in the 1990s [172], and one in Brazil in the 2010s [173]. These were excluded to preserve geographical and epidemiological coherence.

Only prospectively conducted studies were included. Prospective designs allow for systematic and active follow-up, predefined outcome definitions, and contemporaneous outcome recording, all of which are important for the reliable identification of initial cure and subsequent relapse. However, reliance on IPD from clinical trial settings limits model applicability to real-world patients — those who are managed outside trial settings, and may not meet the often-stringent eligibility criteria. These limitations are discussed further in Chapter 7.

A minimum study size was imposed to exclude very small cohorts with unstable relapse estimates. Finally, studies were required to report relapse events during follow-up, either explicitly or in a form that allowed relapse to be inferred from the available IPD.

Participant–Level Criteria

With respect to clinical presentation, treatment response, and outcomes, patients with VL/HIV co-infection constitute an important but distinct clinical population. Accordingly, patients with and without VL/HIV co-infection were *not* combined within a single prediction model, given the substantial uncertainty in extrapolating relapse associations derived from HIV-negative patients to those with VL/HIV co-infection. Since the majority of contributing studies excluded patients with VL/HIV co-infection, insufficient IPD were available to develop a separate model for this group.

As with VL/HIV co-infection, very few contributing studies included pregnant participants, reflecting their systematic exclusion from VL trials and precluding the development of a separate prediction model.

Initial Cure

Understanding study-specific definitions of initial cure is important, as all studies require the patient to demonstrate a treatment response, measured with a test-of-cure, in order to be at subsequent risk of relapse. Consequently, patients *not* achieving initial cure — described as initial treatment failure — should be excluded. A direct consequence of excluding these patients is that model-derived risk estimates are only applicable to patients demonstrating initial cure.

Initial cure definitions based solely on clinical improvement, as is common in routine practice, are likely to classify some patients as cured despite persistently positive tissue aspirates, were these assessed. These patients form a subgroup at increased risk of relapse and would instead be classified as initial treatment failures under more stringent, parasitology-based test-of-cure criteria, thereby being excluded from subsequent follow-up. Consequently, all else being equal, studies applying stricter definitions of initial cure will observe a lower subsequent relapse risk.

Recently, Dahal and colleagues performed a systematic review of the design, conduct, analysis, and reporting of VL therapeutic efficacy studies, published between 2000–2021. Of the 89 studies identified, 71 (79.8%) included parasitological assessment, with or without demonstration of clinical improvement, as part of the test-of-cure, while 13 (14.6%) required clinical improvement only. The remaining studies did not provide a definition. Timing also varied considerably, with the 68 (76.4%) of studies performing the test-of-cure between 15–30 days following treatment completion[88]. Similar patterns are observed in the contributed studies, as reported in the [Supplementary Material](#), and discussed further in subsequent results chapters. Importantly, criteria for ‘clinical improvement’ are often not specified. Further complicating interpretation, many studies describe a subgroup of ‘slow responders’, who remain in the study despite a positive tissue aspirate in the test-of-cure. These patients may undergo repeat assessment at subsequent time points (e.g. 2–4 weeks later), with or without treatment extension, and may or may not ultimately be classified as having achieved initial cure.

Such variation in the initial cure definition can challenge standardisation efforts, leading to differences in observed relapse rates stemming from differences in the population at risk. These differences, however, can often be mitigated through interrogation of the IPD. Box 4.3 provides a working definition for initial cure, which is applied during data harmonisation.

4.2.4 Outcome

Relapse itself, where described at the study-level, is also subject to substantial variation with respect to its (i) definition — including the severity of symptoms required to trigger a repeat aspirate and the tissue type chosen for aspirate, and (ii) timing — including whether patients were actively screened at set time points with clinical examination ± routine aspirates, or whether dependent on patients attending voluntarily based on recurrent symptoms and discharge advice. In line with findings by Dahal et al, a significant proportion of contributing studies do not directly define relapse as a study outcome[88]. Instead, for most studies, a

Box 4.3: IPD-based working definitions

Initial cure Where initial cure (or initial treatment failure) is *not* directly recorded in the IPD as an efficacy outcome, or where it is recorded but the study definition considers ‘slow responders’ as initial treatment failures, it can be inferred from (i) improvement of signs and symptoms between baseline and test-of-cure, and (ii) not requiring rescue treatment during initial treatment. Importantly, reflecting both routine clinical practice and a number of study definitions, detection of parasites at test-of-cure should not preclude the subsequent development of relapse, so long as points (i) and (ii) are met.

Relapse Where relapse is not directly recorded in the IPD as an efficacy outcome, the event can be inferred from two or more of: (i) the need for rescue treatment within 6 months of initial cure assessment (test-of-cure), (ii) the presence of a positive tissue aspirate, and (iii) in addition to a recurrence of compatible signs and symptoms.

relapse event can be inferred from patients achieving initial cure who subsequently do not meet the definition of ‘definite cure’, which itself is typically defined as patients requiring rescue treatment.

Similar to the approach described for identifying patients that achieve initial cure, access to IPD allows relapse events to be inferred from other variables, including: definite cure status, tissue aspirates, timing of rescue treatment initiation, and patient signs and symptoms. Box 4.3 provides an IPD-based working definition of relapse.

Relapse is recorded and modelled as a binary outcome variable (occurred vs. not occurred). Unfortunately, modelling relapse as a time-to-event variable is not feasible, since *timing* information is (i) inconsistently presented across the contributed IPD, and (ii) where presented, is often limited to fixed, predetermined study visits (e.g. 3 months, 6 months).

4.3 Model Development

4.3.1 Sample Size

A common ‘rule of thumb’ is that at least 10–20 outcome events per predictor parameter (EPP) are needed to prevent model overfitting[174, 175]. However, both the validity of this threshold, and the broader premise that a single rule applies universally, have been increasingly debated in the prediction modelling literature[176].

Responding to these concerns, in 2018 Riley et al.[177] proposed a new sample size methodology. For prediction models with binary or time-to-event outcomes,

the approach defines a minimum sample size that satisfies three criteria: (i) minimal optimism in predictor effect estimates, quantified by a global shrinkage factor of ≥ 0.9 ; (ii) a small absolute difference (≤ 0.05) between the model's apparent and adjusted Nagelkerke's R^2 ; and (iii) precise estimation of the overall population risk (i.e. the model intercept). When the number of participants and outcome events is fixed, as in the present study, the maximum allowable EPP can be derived from an estimate of the model's overall performance. In the absence of previously published prediction models for relapse, we followed the authors' recommendation and assumed a Nagelkerke R^2 of 0.15[177].

This methodology has been adopted in the model development presented in this thesis, as implemented in the `pmsampsize` R package[178].

ISC Model

With a total of 228 relapses identified in 4,599 participants (5.0% event rate), the maximum number of predictor parameters satisfying Riley et al.'s three criteria is 25, corresponding to 8.86 EPP. Relaxing the permitted overall shrinkage from 0.90 to 0.85 (modifying criteria (i)) allows for 40 predictor parameters, corresponding to 5.57 EPP.

East Africa Model

With a total of 99 relapses identified in 2,051 participants (4.8% event rate), the maximum number of predictor parameters satisfying Riley et al.'s three criteria is 11, corresponding to 8.81 EPP. Relaxing the permitted overall shrinkage from 0.90 to 0.85 allows for 18 predictor parameters, corresponding to 5.54 EPP.

4.3.2 Candidate Predictors

All model variables, including candidate predictors, are listed in Table 4.1.

For the ISC models, a total of 17 candidate predictor parameters are included (16 when excluding parasite grade), corresponding to a study-specific random intercept term and 12 (11) participant-level candidate predictors, $EPP = 13.41$ (14.25).

For the East Africa models, a total of 14 candidate predictor parameters are included (13 when excluding parasite grade), corresponding to the same variables included in the ISC models minus treatment group, due to convergence issues discussed below, $EPP = 7.07$ (7.62). Full specification of all candidate predictors are presented in Table 4.1.

The following points were considered when selecting candidate predictors:

Variable	Specification (categories)	dof	log	ISC		EA	
				PG	\overline{PG}	PG	\overline{PG}
Relapse (outcome)	Categorical (2)	-	-	✓	✓	✓	✓
Study	Random intercept	1	-	✓	✓	✓	✓
Treatment	Categorical (3)	2	-	✓	✓	✗	✗
Sex	Categorical (2)	1	-	✓	✓	✓	✓
Malnutrition	Categorical (3)	2	-	✓	✓	✓	✓
Anaemia severity	Categorical (2)	1	-	✓	✓	✓	✓
Age	Continuous ¹	3	No	✓	✓	✓	✓
Fever duration	Continuous	1	Yes	✓	✓	✓	✓
WBCs	Continuous	1	Yes	✓	✓	✓	✓
Spleen size	Continuous ²	1	No	✓	✓	✓	✓
Platelets	Continuous	1	Yes	✓	✓	✓	✓
ALT	Continuous	1	Yes	✓	✓	✓	✓
Creatinine	Continuous	1	Yes	✓	✓	✓	✓
Parasite grade ³	Continuous	1	No	✓	✗	✓	✗

¹ Age is modelled as a cubic polynomial.

² A small additive constant (+1) is added to spleen size to allow inclusion of patients with non-palpable spleens.

³ Parasite grade is recorded on a semi-quantitative logarithmic scale, ranging from 1+ to 6+.

Table 4.1: Variables used in the development of the Indian subcontinent (ISC) and East Africa (EA) models. Models are fitted either with parasite grade (PG) or without parasite grade (\overline{PG}). -: not applicable, ✓: included in model, ✗: not included in model, dof: degrees of freedom, log: whether modelled on a natural logarithmic scale, ALT: alanine aminotransferase, WBC: white blood cell.

- To avoid excessive missing data, predictors must be available for at least 50% of participants.
- Predictors should be routinely measured, or at least available for measurement, in the majority of treatment centres in endemic areas.
- Since the model is applied at the time of initial cure, predictors should be available at or *prior* to this time point (typically measured within a month of starting treatment).
- Predictors should be *preferentially* included if (i) they have previously been shown to predict relapse, or (ii) other compelling reasons exist to include — such as expert opinion and arguments supporting a causal association between the predictor and relapse. Discussions in Section 2.3 provide further insight.

- Sample size considerations explored in Section 4.3.1 should guide the maximum number of predictor parameters to prevent model overspecification and overfitting.
- To facilitate model convergence, excessive collinearity should be avoided.

When considering the final point, it is worth highlighting that model convergence issues can occur due to collinearity not only between predictors, but also between predictors and random-effects (clustering) structures. Given the significant heterogeneity in study design and outcome definitions, and further reasons addressed further in Section ??, each contributing study is modelled as a random-intercept term. Consequently, caution must be exercised with categorical predictors that are uniquely, or near-uniquely, identified at the study level.

Treatment

Treatment regimen — already established as an important predictor relapse — represents a categorical predictor affected by collinearity at the study level. For example, including a treatment category of *14 days of paromomycin* in the ISC model would lead to convergence failure when included in a model with study as a random-intercept term. As can be appreciated from Figure 5.2, only one contributing study (Sundar 2009) includes patients receiving this treatment regimen. Consequently, a model including both would not be able to distinguish between relapse risk related to the study or the treatment regimen.⁵

Considering the distribution of treatment regimens across studies within the ISC, treatment will be categorised into three categories that occur in at least three studies (see Table 5.1 and Figure 5.2):

- Single dose liposomal amphotericin B (10mg/kg)
- 28 days miltefosine (standard dose)
- Other

As a consequence of creating a ‘catch-all’ treatment group: *Other*, some of the relationship between treatment and relapse not already accounted for at the study level will be lost. This is an important limitation and addressed further in the discussion (Chapter 7).

⁵Or more technically, this induces near-non-identifiability between the fixed treatment effect and the study-level random intercept, resulting in an ill-conditioned information matrix and failure of numerical optimization.

Table 4.2: Malnutrition severity definitions by age group. BMI(-FA): body–mass–index(–for–age), WFH: weight–for–height, yrs: years, [,]: including range limit, (,): not including range limit

Age group	Metric	Severe	Moderate	Mild/normal
[0, 5) yrs	WFH z-score	($-\infty, -3]$	($-3, -2]$	($-2, \infty)$
[5, 19) yrs	BMI–FA z-score	($-\infty, -3]$	($-3, -2]$	($-2, \infty)$
[19, ∞) yrs	BMI (kg/m^2)	(0, 16)	[16.0, 17.0)	[17, ∞)

Unfortunately, convergence issues preclude the inclusion of treatment as a categorical predictor in the East Africa models. This is not surprising, given fewer participants, fewer studies, and higher treatment–study collinearity when compared to the ISC models (see Figure 6.6). Convergence issues persisted despite exploring different treatment groupings, including separate groups for SSG and SSG/PM combination therapy. Therefore, in the East Africa models, the impact of treatment on relapse risk is incorporated into the study level random intercept.

Malnutrition

Malnutrition is a well-established determinant of progression from asymptomatic infection to clinical VL and of adverse outcomes following initial treatment, including treatment failure and mortality[1, 179]. Evidence linking malnutrition to relapse, however, remains sparse. This may partly reflect the absence of a unified framework for defining malnutrition across age groups, leading to frequent omission or inconsistent classification in prognostic factor and prediction model studies. Anthropometric assessment of malnutrition is inherently age-specific, and no formal guidance exists on how to combine measures across the life course.

We therefore adopt a pragmatic three-level severity scale using age-appropriate metrics (Table 4.2). In children under five years, malnutrition is classified using weight-for-height (WFH) z-scores, largely consistent with WHO guidelines on the definition of acute malnutrition[180]. For individuals aged five to under nineteen years, body–mass–index–for–age (BMI–FA) z-scores are used with identical cut-points, supported by the WHO 2007 growth reference, which was explicitly constructed to ensure continuity with the under-five standards at age five[181]. In adults aged 19 years and over, malnutrition severity is defined using established BMI thresholds. Cole et al. showed that adult BMI cut-offs of 16 and 17 kg/m^2 at 18 years correspond approximately to BMI-for-age z-scores of -3 and -2 in children and adolescents, providing a statistical basis for approximate continuity of severity definitions across

the adolescent–adult boundary[182]. While imperfect, this approach preserves broadly comparable degrees of nutritional deficit across age groups.

For modelling purposes, individuals with mild ($18.5 \leq \text{BMI} < 25 \text{ kg/m}^2$) or obesity ($\text{BMI} \geq 25 \text{ kg/m}^2$), or equivalent z-scores ($z > -1$), were combined into a single *mild/normal* category due to small numbers.

The approach adopted here is consistent with methods used in previous studies of VL outcomes that also use age-specific anthropometric indicators to define pragmatic malnutrition severity groupings[94, 109, 121, 128]. z-scores were calculated using the `anthro` and `anthroplus` R packages for children <5 years and ≥ 5 years, respectively[183, 184].

Anaemia

Anaemia was grouped into two categories: *severe* and *non-severe*, using haemoglobin cut-offs stratified by age and sex thresholds as defined by 2024 WHO guidelines[185]. Additional subdivision of the non-severe anaemia group was limited by the small number of participants in the mild and normal categories.

Age

To account for an anticipated non-linear relationship between age and relapse, age was modelled as a third-degree polynomial term (including linear, squared, and cubic components).

Parasite Grade

Baseline parasite grade, when available, was assessed from splenic, bone marrow, or lymph node aspirates. When reported, the logarithmic counting method of Chulay and Bryceson (1983) was either described or directly cited Additional file 1[51].

Logarithmic Transformations

A number of continuous predictors — including fever duration, spleen length, and all blood tests — were log-transformed to reduce skewness and thus stabilise variance and better approximate normality. For spleen size, +1 was added prior to log-transformation to accommodate zero values and avoid undefined logarithmic results. While recognising that this transformation implicitly assumes that non-palpable spleens can be modelled on the same continuous scale with palpable spleens, the approach was considered a pragmatic solution to avoid model overspecification.

All models assume that the adjusted log(odds) of relapse varies *linearly* with each continuous predictor when transformed as per Table 4.1. These assumptions

are evaluated prior to model fitting through visual assessment of the univariable associations (as described below in Section 4.3.3, and presented in Figure C.17 for the ISC and Figure D.1 for East Africa) and, following model fitting, through inspection of the calibration plots.

4.3.3 Descriptive Analysis

All candidate predictors (pooled and study-specific) are summarised in both tabular and graphical forms.

The correlation between continuous predictors is illustrated with faceted scatter plots using the `ggpairs()` function from the `GGally` R package[186]. The correlation between continuous and categorical predictors is presented with faceted box-and-whisker plots.

Unadjusted relationships between the pooled candidate predictors and the outcome (relapse) are presented in graphical form with 95% confidence intervals. Since this stage of the analysis is exploratory and descriptive, p-values are not presented to avoid multiple hypothesis testing and inflation of type I error, with emphasis instead placed on the shape, magnitude, and uncertainty of observed associations[187].

For continuous predictors (excluding parasite grade), relapse is modelled using a generalized additive model (GAM) with a binomial error distribution and logit link, fitted using the `gam()` function in the R package `mgcv`[188]. The effect of the continuous predictor is represented by a smooth function estimated using penalised thin-plate regression splines. Model fitting is performed by penalised maximum likelihood, with the degree of smoothness selected automatically via restricted maximum likelihood (REML). Both relapse % and log(odds) of relapse are presented, allowing for both direct inspection of the relapse risk and visual assessment of the linearity assumption between the log(odds) of relapse and transformed continuous predictors.

For categorical predictors and parasite grade, relapse is presented using bar charts with 95% confidence intervals calculated using the Wilson method[189].

4.3.4 Missing Data

Data can be missing entirely from a study (systematic missingness), or affecting only certain patients within a study (sporadic missingness). Three principal sources of missing data were identified across both the ISC and East Africa harmonised datasets:

- planned non-capture at the study or site level, often resulting in systematic missingness,
- unplanned incomplete capture of predictors at the study level, resulting in sporadic missingness, and
- incomplete data retrieval, likely resulting in both systematic and sporadic missingness.

Patterns and extent of missingness in candidate predictors were explored and summarised using both tabular and graphical approaches. Study-stratified density plots were used to visualise missingness patterns stratified by study and are presented in the results chapters (Figures 5.7 and 6.7 presented in the Results chapters).

Multiple imputation with chained equations (MICE)⁶ was used to generate multiple imputed datasets[190, 191]. MICE was chosen for its flexibility in accommodating different variable types (continuous, binary, categorical, and count), its suitability for complex data structures including multilevel data, and the availability of well-established software implementations in R, notably the `mice` package and its extensions[192, 193].

Imputation was performed under the missing at random (MAR) assumption, whereby the probability of missingness depends only on observed data[194]. Congeniality between the imputation and analysis models was promoted by (1) including in the imputation model all candidate predictors, the outcome, and variables used to derive predictors (including haemoglobin, height, and weight), and (2) accounting for between-study heterogeneity using a multilevel imputation framework with study included as a random intercept[190]. The imputation methods used are summarised in Table 4.3.

The imputation predictor matrix was initially specified to be saturated and include all variables listed in Table 4.3 as well as variables without missing data (outcome, treatment, and sex), and derived predictors (age polynomial terms, BMI, and anthropometric z-scores). Study was included as a random intercept. Derived predictors were passively imputed from age, weight, and height at the end of each iteration, and, to avoid circularity in the imputation model, were excluded as independent variables when imputing age, weight, and height.

Specification of the imputation model was an iterative process. Candidate imputation models were evaluated with respect to (1) convergence of the chained equations and (2) the extent to which the distributions of imputed values aligned with the corresponding observed data distributions. Model specification and selection

⁶also known as fully conditional specification

Table 4.3: Multiple imputation with chained equations (MICE) methods used for univariable imputation of variables with missing data. ALT: alanine aminotransferase; BMI: body mass index; Crt: creatinine; Hb: haemoglobin; ISC: Indian subcontinent; n/a: not applicable; Plt: platelets; WBC: white blood cell count; WFH: weight-for-height.

Method	Variables	Description	R package
2l.lmer	age, weight, height, fever duration, all bloods (Hb, ALT, WBC, Plt, Crt), spleen size	Two-level normal model using <code>lme4::lme4()</code>	<code>mice</code> [192] <code>micemd</code> [195]
2l.zip	parasite grade (East Africa only)	Two-level zero-inflated Poisson model using Bayesian estimation	<code>countimp</code> [196]
2l.poisson	parasite grade (ISC only)	Two-level Poisson model using Bayesian estimation	<code>countimp</code> [196]
Passive imputation	BMI, BMI-for-age z-score, WFH z-score, age ² , age ³	Calculated during imputation from age, weight and height.	<code>mice</code> [192]
n/a	outcome, treatment (ISC only), sex, study (random intercept term)	No imputation performed (no missing data)	n/a

were informed by visual inspection of diagnostic plots, including trace plots of the mean and standard deviation of imputed values across iterations, density plots comparing observed and imputed distributions, and scatter plots comparing observed and imputed data for key anthropometric relationships (weight versus height, weight versus age, and height versus age). Diagnostic plots are included in the [Supplementary Material](#). On visual inspection of the trace plots, twenty iterations per imputation were considered more sufficient to reach stable convergence.

Parasite grade was modelled as count data. One unit was subtracted from the original grading scale (1+ to 6+) to permit zero values. Model selection for parasite grade differed by geographical region. In the ISC dataset, a Poisson model provided the best fit to the observed data. In contrast, for the East Africa dataset, a zero-inflated Poisson model better captured the excess of 1+ grades.

For each model development dataset, 30 imputations were generated with 20 iterations per imputation. This represented a balance between computational feasibility and the need to stabilise parameter estimates. As a general rule, it has been stated that the number of imputations should at least match the percentage of incomplete cases[190]. For datasets with many variables, however, van Buuren suggests that this requirement can be relaxed such that the minimum number of imputations approximates the average missing data rate[192]. The average missing data rates across candidate predictors were 14.3% for the ISC dataset and 14.9% for the East Africa dataset, whilst the proportion of cases with any missing data was over 80%. Since 80 iterations was considered too computationally intensive, a compromise of 30 imputations was chosen.

Unless specified otherwise, subsequent analyses were performed separately within each imputed dataset, with results pooled across imputations using Rubin's Rules[194].

Grouping of anaemia severity and malnutrition status was performed after imputation, as described in Section 4.3.2.

4.3.5 Model Specification

Relapse was modelled using a multivariable generalised linear mixed-effects model (GLMM) with a logit link function. Predictors were transformed as previously described. Following the aforementioned transformations, continuous predictors were centred and scaled by their means and standard deviations, respectively, to improve model stability. Anticipated between-study heterogeneity was accounted for by including study as a random intercept term[197]. While introducing significant methodological complexity, a number of benefits gained by accounting for between-study heterogeneity[155]:

- Ignoring clustering can result in relapse probability estimates that are biased towards the pooled population estimate[198].
- Variation in model performance measures can be compared and contrasted across the included studies, allowing insights into sources of heterogeneity[199].
- Allows for improved generalisability of the model to new settings and populations[155, 199].

GLMMs were fitted using the `glmer()` function from the `lme4` R package[200]. This approach estimates fixed effects while accounting for random effects by maximizing the marginal likelihood, which integrates over the random-effects distribution. For GLMMs, this integration cannot be solved exactly and is approximated using the Laplace approximation for binomial outcomes. Model parameters were estimated using maximum likelihood. To enhance model stability and improve convergence, optimization was performed using the `nloptwrap` optimizer with an increased number of iterations and strict convergence criteria (maximum evaluations = 200,000; absolute tolerances for the objective function and parameters = 1×10^{-8}).

The saturated ISC model (with parasite grade and treatment groups included) is presented in Box 4.4. For the East Africa models, the treatment group predictors are omitted due to collinearity at the study level, as previously discussed. For both ISC and East Africa, models are also fitted without parasite grade, given its frequent absence from routine clinical practice.

4.3.6 Variable Selection

The final predictor set was determined using backwards variable selection with cutoff $p < 0.10$. Univariable selection was avoided to prevent exclusion of predictors that may demonstrate significance only in the presence of other predictors, and to reduce the risk of overfitting[201].

A variety of methods have been explored for performing variable selection with multiple imputed datasets[202, 203]. In accordance with recommendations by Austin et al. and Wood et al., Rubin's Rules were used to combine p-values for predictor significance at each selection stage across the imputed datasets. At each stage, the full model is fitted in each of the 30 imputed datasets and the estimated regression coefficients and their standard errors are pooled using Rubin's Rules. The candidate predictor with the highest pooled p-value above the 0.10 threshold was removed, and the process repeated until all remaining predictors had pooled p-values below 0.10[194, 202, 203]. For categorical predictors with over two groups (malnutrition, treatment), predictor significance was assessed with the D1 multivariate Wald test as implemented in the `mice` R package[192, 204]. For age, lower-order polynomial terms were retained in the model whilst higher-order terms remained.

Variable selection was performed in a bespoke R script, available in the [Supplementary Material](#).

Box 4.4: Saturated model specification

$$\log \left(\frac{\Pr(Y_{ij} = 1)}{\Pr(Y_{ij} = 0)} \right) = \beta_0 + \beta_{\text{sex}} \cdot \text{sex}_{ij} + \beta_{\text{age}} \cdot \text{age}_{ij} + \beta_{\text{age}^2} \cdot \text{age}_{ij}^2 + \beta_{\text{age}^3} \cdot \text{age}_{ij}^3 + \beta_{\text{treat-sda}} \cdot \text{treat-sda}_{ij} + \beta_{\text{treat-oth}} \cdot \text{treat-oth}_{ij} + \beta_{\text{mal-mod}} \cdot \text{mal-mod}_{ij} + \beta_{\text{mal-sev}} \cdot \text{mal-sev}_{ij} + \beta_{\text{anaemia-sev}} \cdot \text{anaemia-sev}_{ij} + \beta_{\text{fever-dur}} \cdot \text{fever-dur}_{ij} + \beta_{\text{spleen-cm}} \cdot \text{spleen}_{ij} + \beta_{\text{para}} \cdot \text{para}_{ij} + \beta_{\text{wbc}} \cdot \text{wbc}_{ij} + \beta_{\text{plat}} \cdot \text{plat}_{ij} + \beta_{\text{alt}} \cdot \text{alt}_{ij} + \beta_{\text{creat}} \cdot \text{creat}_{ij} + \mu_j.$$

Where: i represents the i th participant in study j , Y is the relapse outcome ($1 =$ relapse, $0 =$ no relapse), and

$$Y_{ij} \sim \text{Bernoulli}(E[Y_{ij}]) \\ \mu_j \sim \mathcal{N}(0, \tau^2).$$

β_0 is the fixed model intercept, and β_k are the fixed effect coefficients for each candidate predictor k , corresponding to sex ($1 =$ male, $0 =$ female), age, treatment group (reference = standard dose miltefosine, **treat-sda**: 10mg/kg single dose liposomal amphotericin B, **treat-oth**: other), malnutrition severity (reference = mild/normal, **mal-mod**: moderate, **mal-sev**: severe), anaemia severity ($1 =$ severe, $0 =$ non-severe), fever duration, spleen size, **para**: parasite grade, **wbc**: white blood cell count, **plat**: platelet count, **alt**: alanine transaminase, and **creat**: creatinine. The random intercept μ_j captures between-study heterogeneity, with variance τ^2 . All continuous candidate predictors, except age, spleen size, and parasite grade, are log-transformed, centred by their mean, and scaled by their standard deviation. Age is centred and scaled, and modelled as a third-degree polynomial term. Spleen size is log-transformed after adding +1.

4.3.7 Model Performance

In accordance with the TRIPOD–Cluster reporting guidelines, measures of calibration and discrimination are presented for the prediction models overall and for each study (cluster) separately[155]. Wynants et al. address a number of decisions that must be made when evaluating prediction model performance in clustered data[198]. As described by Wynants et al, within-study (conditional) performance measures are presented reflecting model performance when evaluated at the study level[198, 205]. Assessment of model performance heterogeneity across studies is presented with forest plots using a combination of fixed and random effects meta-analyses[162, 205].

Discrimination

Model discrimination was assessed using the c (concordance)–statistic. For models with binary outcomes, the c–statistic is equivalent to the AUC, and is the probability that a randomly selected case (patient who experiences a relapse event) has a higher predicted relapse probability than a randomly selected non–case (patient who does not experience a relapse event).

Study–specific c–statistics were estimated for each imputed dataset using the R package: `pROC`[206]. Standard errors and 95% confidence intervals were calculated using the bootstrap method with 2000 resamples.

As suggested by Burgess et al., study–specific c–statistics were first pooled across imputed datasets using Rubin’s Rules *prior* to estimating the summary (overall) c–statistic using meta–analysis[207]. As recommended by van Klaveren et al.[205] and Debray et al.[162], overall c–statistics are estimated using a random–effects meta–analysis approach. Between–study variance (τ^2) is estimated using restricted maximum likelihood (REML), and variance of the pooled c–statistic is estimated with the Hartung-Knapp-Sidik-Jonkman method[208].

For comparison, a fixed–effects meta–analysis approach to estimating the overall c–statistic is also presented, weighted by the number of event/non–event pairs in each study. This estimate is equivalent to the c–statistic obtained from comparing pairs of events and non–events within the same study only[198, 209].

Given the often small number of relapses in individual studies, estimates of study–specific c–statistic uncertainty (variance, confidence intervals) are likely to be imprecise and should be interpreted cautiously. To reduce potential bias introduced from small sample sizes, only studies with >5 events are included in the meta–analyses[210, 211].

Calibration

Model calibration assesses agreement between predicted and observed relapse probability, and was evaluated with calibration plots, calibration slope, and calibration intercept (calibration-in-the-large, CITL). Calibration slope and intercept are estimated conditional on the study, and represent within–study performance measures[198].

Calibration intercept describes whether a model’s average predicted risk differs from the overall observed event rate. A positive intercept indicates that the model systematically underestimates relapse risk, whilst a negative intercept indicates systematic overestimation. The calibration intercept is estimated by fitting a logistic

GLMM with relapse as the outcome, study as a random intercept, and the linear predictor from the original model as an offset term. The estimated fixed intercept then corresponds to the within-study calibration intercept, with an expected value of zero when assessed in the development dataset (apparent performance)[198].

Calibration slope assesses whether a model's predicted risks are systematically too extreme or too conservative. A slope of 1 indicates perfect calibration and is the expected value when evaluating apparent performance in the development dataset. Values less than 1 indicate overfitting (overly extreme predictions), and values greater than 1 indicate underfitting (overly moderate predictions). It was estimated by fitting a further logistic GLMM with relapse as the outcome, study as a random intercept, and the linear predictor from the original model included as both a fixed and random effect (i.e. a random slope term)[198]. In this formulation, the fixed effect of the linear predictor represents the within-study calibration slope. To mitigate model convergence issues arising from the inclusion of studies with small sample sizes, we adopted a Bayesian approach. Parameters were estimated using the Hamiltonian Monte Carlo algorithm as implemented in Stan, accessed via the R package `brms`[212, 213]. Posterior sampling was conducted using four chains with 2,500 iterations per chain (including warm-up), and the target acceptance rate was increased (`adapt_delta = 0.95`) to reduce divergent transitions. Default weak priors were used.

Heterogeneity in calibration slope and intercept across studies is summarised using a the same random effects approach to that described for the c-statistic. Study-specific estimates were initially calculated within each imputed dataset prior to pooling across imputations using Rubin's Rules[207]. Summary measures were then estimated using random-effects meta-analysis with REML estimation of between-study variance and Hartung-Knapp-Sidik-Jonkman confidence intervals[208].

Calibration plots allow direct visual assessment of the relationship between observed (y -axis) and predicted (x -axis) relapse probabilities. Firstly, all imputed datasets were stacked into a single dataset. Predicted relapse probabilities were then calibrated to each study using logistic recalibration of the intercept and divided into deciles. Observed probabilities were calculated for each decile and 95% confidence intervals estimated using Wilson's method[189]. The smoothed relationship between observed and predicted relapse probabilities was estimated using a generalised additive model, as previously described. To account for the stacking of 30 imputed datasets, all standard errors were inflated by $\sqrt{30}$.

Following the same methodology for standard calibration plots, calibration was also illustrated for selected predictor subgroups by plotting both observed and predicted probabilities on the y -axis against predictor subgroups on the x -axis.

4.4 Internal Validation

Internal validation is performed using bootstrap resampling with 500 bootstrap samples. Bootstrapping evaluates all aspects of the model building process to quantify and adjust for overfitting and optimism in model performance[157]. Bootstrapping is performed at the overall patient, which as described by Bouwmeester et al., provides accurate optimism estimates in clustered data[214].

For each of the 500 bootstrap samples of the original dataset, all aforementioned model development steps, including multiple imputation and variable selection, were undertaken (see Figure 4.1). For each of the resulting 500 bootstrap models, pooled performance measures were evaluated across (i) the imputed bootstrap datasets used to derive the bootstrap model and (ii) the imputed original datasets used to derive the original model. The mean pooled performance differences between (i) and (ii) were then subtracted from the original model apparent performance measures to obtain the optimism-adjusted performance measures. Uniform shrinkage of the parameter estimates was performed by multiplying the fitted regression coefficients by the optimism-adjusted calibration slope and re-estimating the model intercept with logistic recalibration.

Given the computational intensity of the model development process, bootstrap validation was implemented using a high-performance computing cluster based in the Nuffield Department of Medicine at the University of Oxford.⁷

4.5 Summary

In summary, this chapter has described the methods used to develop and internally validate four prognostic models for six-month VL relapse (HIV-negative patients) using IPD from the IDDO VL platform: two models for the ISC (with and without baseline parasite grade) and two analogous models for East Africa.

Contributed datasets were standardised to the CDISC-SDTM format, converted to a single analysis-ready dataset, and filtered using pre-specified study- and participant-level eligibility criteria that ensure the population at risk comprises patients who achieved an initial cure. Candidate predictors were selected based on clinical relevance and data availability, and were transformed as appropriate (e.g. logarithmic or polynomial transformations). Predictor specification was informed by considerations of collinearity, including grouping of treatment variables to reduce study-level dependence and support model convergence. Sample-size

⁷<https://www.medsci.ox.ac.uk/for-staff/resources/bmrc>

considerations followed the framework of Riley et al. to guide the maximum allowable degrees of freedom.

Modelling used multivariable GLMMs with study as a random intercept, fitted on multiply imputed datasets (MICE, 30 imputations, multilevel imputation with study random intercept and diagnostics to check plausibility). Backwards selection (pooled p-values, cutoff $p < 0.10$) determined the final predictor set, with coefficients and uncertainty combined with Rubin's rules at each variable selection stage. Internal validation applied full bootstrap resampling ($b = 500$), repeating multiple imputation and selection within each bootstrap to quantify optimism. The final models were uniformly shrunk by the optimism-adjusted calibration slope.

5

Results: Indian Subcontinent Models

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5.1 Descriptive Analysis

On application of the eligibility criteria to the IDDO VL data platform, a total of 19 studies and 4,599 patients were selected for inclusion. A flow diagram is presented in Figure 5.1.

5.1.1 Study Characteristics

Key characteristics of the 19 included studies are presented in Table 5.1.

A median of 144 patients were recruited in each study, ranging from 6 to 928 patients (IQR: 86.5 to 329.5 patients). Patients were recruited between 2000 and 2017 from sites in India (15 studies, 4,171 [90.7%] patients)[63, 66, 70, 92, 215–225] and Nepal (4 studies, 428 [9.3%] patients)[226–229]. All Indian studies recruited patients from the state of Bihar in northeastern India, with the majority of studies led by investigators from either a government referral hospital in Patna (Rajendra

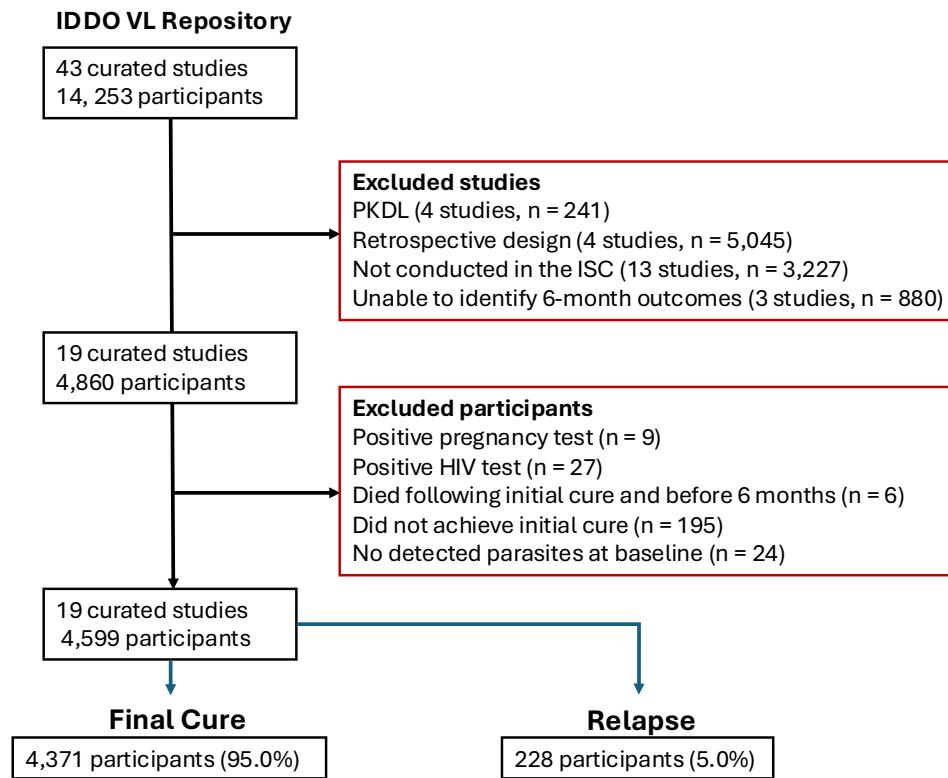


Figure 5.1: Flow diagram showing the studies and patients excluded from Indian subcontinent model development. HIV: human immunodeficiency virus; IDDO: Infectious Diseases Data Observatory; ISC: Indian subcontinent; PKDL: post kala-azar dermal leishmaniasis; VL: visceral leishmaniasis.

Memorial Research Institute of Medical Sciences: RMRIMS) (4 studies, 1,125 [24.5%] patients)[63, 216–218], or a private research facility in Muzaffarpur (Kala-azar Medical Research Centre: KAMRC) (9 studies, 2,652 [57.7%] patients)[66, 92, 215, 219–223, 225]. All Nepalese studies were led by investigators based at the B.P. Koirala Institute of Health Sciences, a health sciences university in the city of Dharan, Koshi Province, eastern Nepal.

Table 5.1: Key characteristics of included studies, ordered by lead author and year of publication/protocol. Where information not presented in the publication, information is extracted from the study protocol. Total patient number, number of relapses, and treatment arms reflect information provided in the contributed datasets. -: not reported; ABLE: Amphotericin B lipid emulsion (Bharat Serum and Vaccines Ltd.); alt.: alternative; ABD: Amphotericin B deoxycholate; BD: twice daily (bis die); BMGF: Bill and Melinda Gates Foundation; BPKIHS: B.P. Koirala Institute of Health Sciences; D: Day(s); EC: European Commission; Govt.: Government; ICMR: Indian Council of Medical Research; IM: Intramuscular; KAMRC: Kala-azar Medical Research Center; LAMB: Liposomal amphotericin B (Gilead formulation unless otherwise specified); MF: Miltefosine; mg/kg: milligrams per kilogram; NCVBDC: National Center for Vector Borne Diseases Control; OD: once daily (omni die); P: Publication; PATH: Program for Appropriate Technology in Health; PO: per os (oral); PM: Paromomycin; Pr: Protocol; Ref: Reference; RMRIMS: Rajendra Memorial Research Institute of Medical Sciences; SSG: Sodium stibogluconate; TDR: UNICEF/UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases; UN: United Nations; WHO: World Health Organization

Study ¹	Title	Journal	Sponsor/funding	Location(s)	Study design	Study arm(s)	Age (years)	Study period	n (model)	Relapses (%)
Bhattacharya 2007[63]	Phase 4 trial of miltefosine for the treatment of Indian visceral leishmaniasis	J Infect Dis	ICMR	13 locations in Bihar, India (outpatient setting)	Open label; phase 4; safety/efficacy	(1) MF, PO, 28D, dosed according to age and weight ^{2,3}	2–65	2002–2004	352 ⁴	22 (6.3)
Chakraborty 2008[215]	Human placental extract offers protection against experimental visceral leishmaniasis: a pilot study for a phase-I clinical trial	Am J Trop Med Hyg	Indian Council of Scientific and Industrial Research; Albert David Ltd.	KAMRC, Muzaffarpur, India	“Pre-phase 1”; pilot/preliminary	(1) Human placental extract, 2.06mg, IM, single dose; (2) ABD, 1mg/kg, IV, alt. days for 30D ⁵	≥5	2003–2005	6	0 (0)
Das 2009[216]	A controlled, randomized nonblinded clinical trial to assess the efficacy of amphotericin B deoxycholate as compared to pentamidine for the treatment of antimony unresponsive visceral leishmaniasis cases in Bihar, India	Ther Clin Risk Manag	-	RMRIMS, Patna, India	Randomised; open label; efficacy	(1) ABD, 1mg/kg, IV, alt. days for 30D; (2) pentamidine, 4mg/kg, IM, alt. days for 30D	6–60	2002	73	5 (6.8)
Koirala 2003[229]	Phase IV trial of miltefosine in the treatment of visceral leishmaniasis	Protocol only	-	BPKIHS, Dharan, Nepal	Open label; phase 4; safety/efficacy	(1) MF, PO, 28D, dosed according to age and weight ^{2,3}	2–65	2003–2004	116	12 (10.3)
Pandey 2016[217]	Pharmacovigilance of miltefosine in treatment of visceral leishmaniasis in endemic areas of Bihar	Am J Trop Med Hyg	NCVBDC, Govt. of India; World Bank	4 locations in Bihar, India	Open label; safety/efficacy	(1) MF, PO, 28D, dosed according to age and weight ^{2,6}	6–70	2012–2015	600	45 (7.5)
Pandey 2017[218]	Efficacy and safety of liposomal amphotericin B for visceral leishmaniasis in children and adolescents at a tertiary care center in Bihar, India	Am J Trop Med Hyg	-	RMRIMS, Patna, India	Open label; safety/efficacy	(1) LAMB, 10mg/kg, IV, single dose	<15	2014–2016	100	2 (2.0)

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Table 5.1: continued

Study ¹	Title	Journal	Sponsor/funding	Location(s)	Study design	Study arm(s)	Age (years)	Study period	n (model)	Relapses (%)
Rijal 2003[226]	Treatment of visceral leishmaniasis in south-eastern Nepal: decreasing efficacy of sodium stibogluconate and need for a policy to limit further decline	Trans R Soc Trop Med Hyg	WHO, Geneva University Hospital; Novartis Foundation	BPKIHS, Dharan, Nepal	Non-randomised; efficacy	SSG, 20mg/kg, IV/IM, ⁷ OD, 30D, extended to 40D if positive aspirate at 30D. Either (1) in hospital or (2) first 5–7 days in hospital;	All	2000–2001	102	1 (1.0)
Rijal 2010(A)[227]	Efficacy and safety of liposomal amphotericin B in Nepalese patients with visceral leishmaniasis	Protocol only	TDR	BPKIHS, Dharan, Nepal	Phase 2/3; safety/efficacy	(1) LAMB, 3mg/kg, IV, OD, D1–5 (21mg/kg total dose)	12–65	2010–2011	32	1 (3.1)
Rijal 2010(B)[228]	Clinical risk factors for therapeutic failure in kala–azar patients treated with pentavalent antimonials in Nepal	Trans R Soc Trop Med Hyg	EC (5th Framework Programme)	BPKIHS, Dharan, Nepal	Prospective cohort	(1) SSG, 20mg/kg, IV/IM, ⁷ OD, 30D	-	2001–2003	178	1 (0.6)
Sundar 2007[70, 230]	Injectable paromomycin for visceral leishmaniasis in India	N Engl J Med	PATH (including UN, BMGF, TDR)	4 locations in Bihar, India	Randomised; open label; phase 3; non-inferiority; safety/efficacy	(1) PM, 15mg/kg, IM, OD, 21D; (2) ABD, 1mg/kg, IV, alt. days for 30D	5–55	2003–2004	250 ⁴	4 (1.6)
Sundar 2008(A)[219, 231]	New treatment approach in Indian visceral leishmaniasis: single-dose liposomal amphotericin B followed by short-course oral miltefosine	Clin Infect Dis	Banaras Hindu University	KAMRC, Muzaffarpur, India	Partially randomised; open label; phase 2; non-comparative; sequential; triangular	LAMB, 5mg/kg, IV, single dose, either (1) alone, or (2,3,4) in combination with MF, 50mg, PO, BD, D2–9, D2–11, or D2–15; and (5) combination of LAMB, 3.75mg/kg, IV, single dose, and MF, 50mg, PO, BD, D2–15	≥12	2006–2007	225	7 (3.1)
Sundar 2008(B)[220]	Safety of a pre-formulated amphotericin B lipid emulsion for the treatment of Indian kala–azar	Trop Med Int Health	Bharat Serum and Vaccines Ltd.	KAMRC, Muzaffarpur, India	Non-randomised; non-comparative; open label; phase 2; safety/efficacy	ABLE, IV, OD, 3D at (1) 5mg/kg (2) 4mg/kg, or (3) 3mg/kg	12–65	2004–2005	45	4 (8.9)
Sundar 2009[221, 232]	Short-course paromomycin treatment of visceral leishmaniasis in India: 14-day vs 21-day treatment	Clin Infect Dis	Banaras Hindu University	KAMRC, Muzaffarpur, India	Randomised; open label; phase 3; safety/efficacy	PM, 15mg/kg, IM, OD, either (1) 14D or (2) 21D	5–55	2007–2008	307	26 (8.5)
Sundar 2010[222, 233]	Single-dose liposomal amphotericin B for visceral leishmaniasis in India	N Engl J Med	Banaras Hindu University	KAMRC, Muzaffarpur, India	Randomised; open label; phase 3; safety/efficacy	(1) ABD, 1mg/kg, IV, alt. days for 30D; (2) LAMB, 10mg/kg, IV, single dose	2–65	2008–2009	412	14 (3.4)

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Table 5.1: continued

Study ¹	Title	Journal	Sponsor/funding	Location(s)	Study design	Study arm(s)	Age (years)	Study period	n (model)	Relapses (%)
Sundar 2011[223, 234]	Ambisome plus miltefosine for Indian patients with kala-azar	Trans R Soc Trop Med Hyg	Banaras Hindu University	KAMRC, Muzaffarpur; RMRIMS, Patna, India	Open label; phase 2; safety/efficacy	(1) LAMB, 5mg/kg, IV, single dose, with MF, 2.5mg/kg/day, PO, D2-D15 ⁸	2-65	2007-2009	128	5 (3.9)
Sundar 2012[66]	Efficacy of miltefosine in the treatment of visceral leishmaniasis in India after a decade of use	Clin Infect Dis	EC (Kaladrug-R); Sitaram Memorial Trust	KAMRC, Muzaffarpur, India	Open label; safety/efficacy	(1) MF, PO, 28D, dosed according to age and weight ^{2, 3}	6-70	2009-2010	571	34 (6.0)
Sundar 2014[224, 235]	Efficacy and safety of amphotericin B emulsion versus liposomal formulation in Indian patients with visceral leishmaniasis: a randomised, open-label study	PLoS Negl Trop Dis	Bharat Serums and Vaccines Ltd; Department of Science and Technology, Govt. of India	4 locations in Bihar, India.	Randomised; open label; phase 3; safety/efficacy	(1) LAMB, 15mg/kg, IV, single dose; (2) ABLE, 15mg/kg, IV, single dose	5-65	2009-2011	144 ⁴	9 (6.3)
Sundar 2015[225, 236]	Single-dose indigenous liposomal amphotericin B in the treatment of Indian visceral leishmaniasis: A phase 2 study	Am J Trop Med Hyg	Lifecare Innovations; Department of Science and Technology, Govt. of India	KAMRC, Muzaffarpur, India	Non-randomised; non-comparative; open label; phase 2; safety/efficacy	LAMB (Lifecare Innovations), IV, single dose (1) 10mg/kg or (2) 15mg/kg	12-60	2012-2013	30	3 (10.0)
Sundar 2019[92, 237]	Effectiveness of single-dose liposomal amphotericin B in visceral leishmaniasis in Bihar	Am J Trop Med Hyg	Banaras Hindu University	KAMRC, Muzaffarpur, India	Observational; efficacy	(1) LAMB, 10mg/kg, IV, single dose	All	2013-2017	928	33 (3.6)

¹ Study name is composed of the lead author and year of publication or most recent protocol.² Miltefosine dosing (i) ≥12 years and ≥25kg: 50mg BD; (ii) ≥12 years and <25kg: 50mg OD; (iii) <12 years and <25kg: 2.5mg/kg/day.³ Dosing in <12 years and <25kg: in divided doses⁴ Contributed number of participants from KAMRC site only.⁵ ABD arm not presented in publication.⁶ Dosing in <12 years and <25kg: not further described.⁷ Dosing not further described.⁸ SSG route of administration (IV vs IM) not specified.

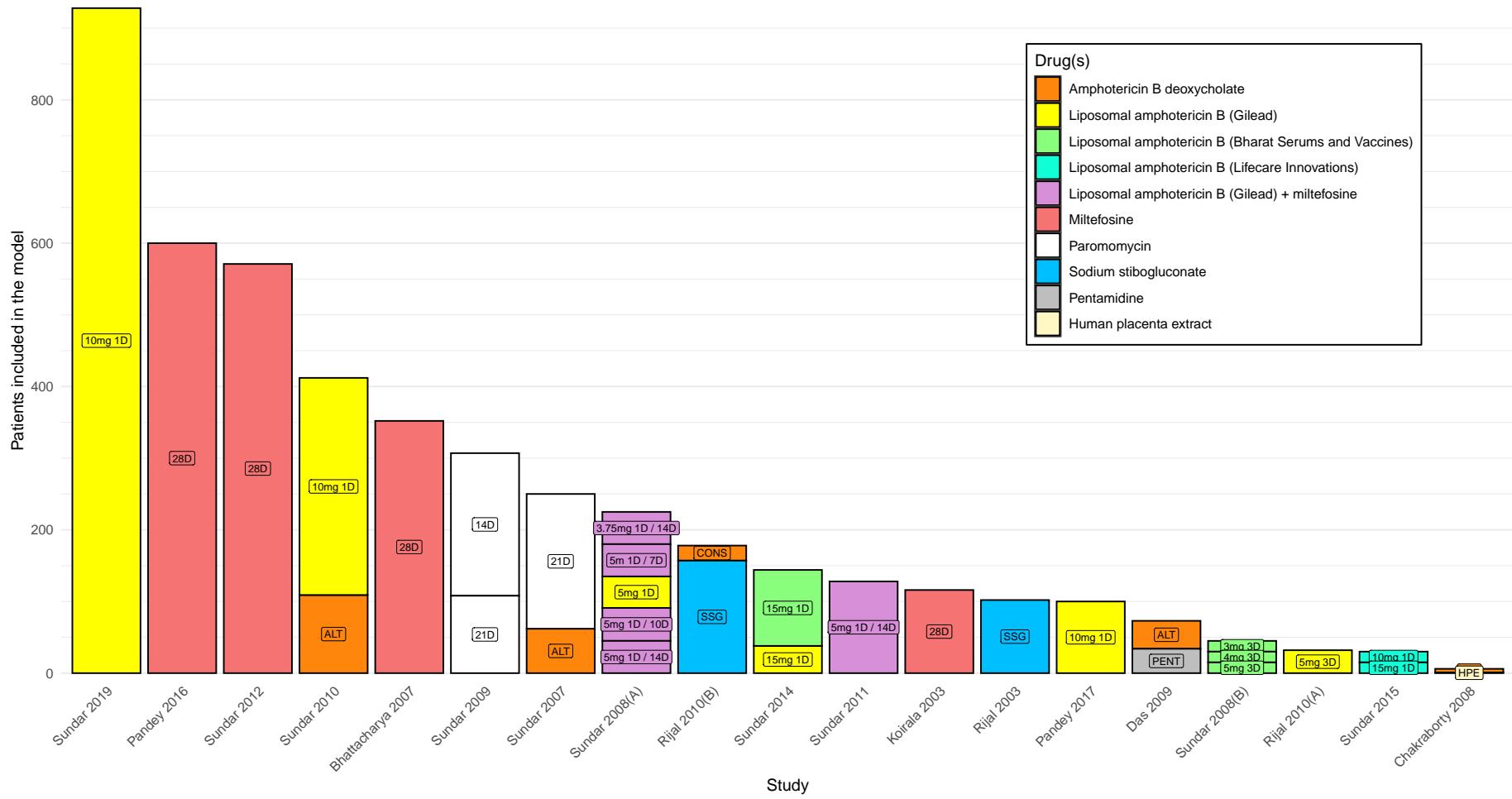


Figure 5.2: Bar chart showing the distribution of treatment regimens across contributing studies from the Indian subcontinent. Important distinguishing dosing information are provided in the overlaying labels, as space allows. Full treatment details are presented in Table 5.1. 6 patients are included from Chakraborty 2008: 5 receiving alternate day amphotericin B deoxycholate and 1 receiving human placenta extract. ABD: amphotericin B deoxycholate; ALT: alternate days; CONS: consecutive days; D: days; HPE: human placenta extract; MF: miltefosine; PENT: pentamidine; mg: milligrams/kilogram; SSG: sodium stibogluconate.

Study Design and Treatment Arms

Study designs are summarised in Table 5.1 as described in the publication or protocol. Four studies (428 [9.3%] patients) were described as Phase 2 trials[219, 220, 223, 225], four studies (1,113 [24.2%] patients) as Phase 3 trials[70, 221, 222, 224], two studies (468 [10.2%] patients) as Phase 4 trials[63, 229], and one study (32 [0.7%] patients) as a Phase 2/3 trial[227].

Ten studies (1,625 [35.3%] patients) allocated patients to more than one treatment arm[70, 215, 216, 219–222, 224, 225, 228], of which six studies (1,411 [30.7%] patients) were randomised[70, 216, 221, 222, 224] or partially randomised[219].

Treatment arms are summarised by study in Figure 5.2. The three largest studies were all monotherapy trials that treated with either 10mg/kg single dose liposomal amphotericin B (1 study, 928 [20.2%] patients)[92], or 28-day miltefosine (2 studies, 1,171 [25.5%] patients).

Figure 5.2 presents the different treatment regimens across all studies.

Study Eligibility Criteria

All studies recruited both male and female patients, and all but three studies restricted inclusion by age. Four studies only recruited patients aged 12 years and above (314 [6.8%] patients)[219, 220, 225, 227]. Where specified, the *lower* age limit was otherwise between 2 and 6 years. One study (100 [2.2%] patients) recruited children only (<15 years)[218]. Otherwise, the *upper* age limit ranged between 60 and 70 years.

In the 16 studies that included baseline haemoglobin level in their eligibility criteria, the median threshold was 50g/dL (range 35 to 60g/dL).¹ Almost all studies excluded patients with serious illness or the presence of significant co-existing diseases. No study explicitly excluded patients based on malnutrition severity.

Twelve studies (2,021 [43.9%] patients) explicitly reported performing HIV testing on all recruited patients[63, 65, 70, 215, 219–222, 224, 225, 227, 229], and patients with confirmed VL/HIV co-infection were excluded from all but two studies (280 [6.1%] patients)[226, 228]. Patients with HIV/VL co-infection from these two studies were excluded at the IPD level, where reported.

Inclusion criteria based on prior VL treatment were reported in 12 studies (2,629 [57.2%] patients)[70, 92, 216, 220–228], with timing since last VL treatment ranging from 10 days[220] to lifelong[92]. One study (73 [1.6%] patients) only recruited patients who had failed treatment with SSG[216].

¹with one study reporting boosting haemoglobin with blood transfusions prior to recruitment[216].

Specific wording of the inclusion and exclusion criteria, and exclusion thresholds for platelets, white blood cells, clotting, renal, and liver function, are provided in the [Supplementary Material](#).

Diagnostic Criteria

The majority of studies specified clinical criteria for inclusion, with six studies (1,984 [43.1%] patients) requiring ≥ 2 weeks' fever and splenomegaly[[92](#), [217](#), [224](#), [226–228](#)]. The remaining studies either did not specify clinical criteria (two studies, 36 [0.8%] patients)[[215](#), [225](#)], or referred more generally to the presence of typical signs and symptoms (11 studies, 2,579 [56.1%] patients).

VL was confirmed by tissue aspirate in all but two studies (1,528 [33.2%] patients)[[92](#), [217](#)], where the rK39 RDT was instead used as the primary diagnostic method. Three studies (276 [6.0%] patients)[[218](#), [224](#), [227](#)], screened patients with the rK39 RDT prior to confirmation with a tissue aspirate.

Relapse

Nine studies directly defined relapse in their publications or protocols[[63](#), [70](#), [92](#), [216](#), [218](#), [226–229](#)]. In the remaining studies, relapse events could be inferred indirectly from definitions of initial cure and treatment failure/success. Confirmation with tissue aspirates was performed in 13 studies, and reported (at least partially) in the IPD in 12 studies (see [Supplementary Material](#) for study-specific details).

In the three studies that reported relapse beyond 6 months[[92](#), [219](#), [228](#)], IPD interrogation allowed identification of the subset of patients where relapse occurred within 6 months of initial cure assessment. Active follow-up strategies were used to identify relapse events in all but one study (928 [20.2%] patients)[[92](#)].

Initial Cure

Initial cure was assessed 28–30 days after treatment initiation in 14 studies (3,740 [81.3%] patients)[[63](#), [66](#), [92](#), [215–218](#), [222–226](#), [228](#), [229](#)]. In the remaining five studies, initial cure was assessed either at two different time points depending on the treatment arm (two studies, 532 [11.6%] patients)[[70](#), [221](#)], or between days 16 and 19 (three studies, 302 [6.6%] patients)[[219](#), [220](#), [227](#)]. Clinical criteria for initial cure were described in all but two studies[[63](#), [215](#)], although often loosely defined (see [Supplementary Material](#) for study-specific details).

Tissue aspirate formed part of the initial cure assessment in all but one study (928 [20.2%] of patients without tissue aspirate)[[92](#)]. In nine studies (1,378 [30.0%]

patients)[63, 70, 220, 221, 224–227, 229], patients with an initial 1+ parasite grade underwent a repeat aspirate 10 to 60 days later. If the repeat aspirate were negative, the patient would often be considered a ‘slow-responder’, allowing progression to either definite cure or relapse.

5.1.2 Patient Characteristics

Overall (marginal) distributions of categorical and continuous variables are tabulated in Tables 5.2 and 5.3, respectively. These distributions are also displayed graphically in Figure 5.4 for bar charts of categorical variables, and Figures 5.6 and 5.5 for histograms of non-laboratory and laboratory variables, respectively. Study-specific distributions are presented for age, sex, and relapse in Figure 5.3. In the Appendix, study-specific distributions of all categorical and continuous variables are presented in Figures C.1 and C.2–C.14, respectively.

Patient numbers and proportions presented in this section exclude missing data. See Section 5.1.4 for further information on missing data.

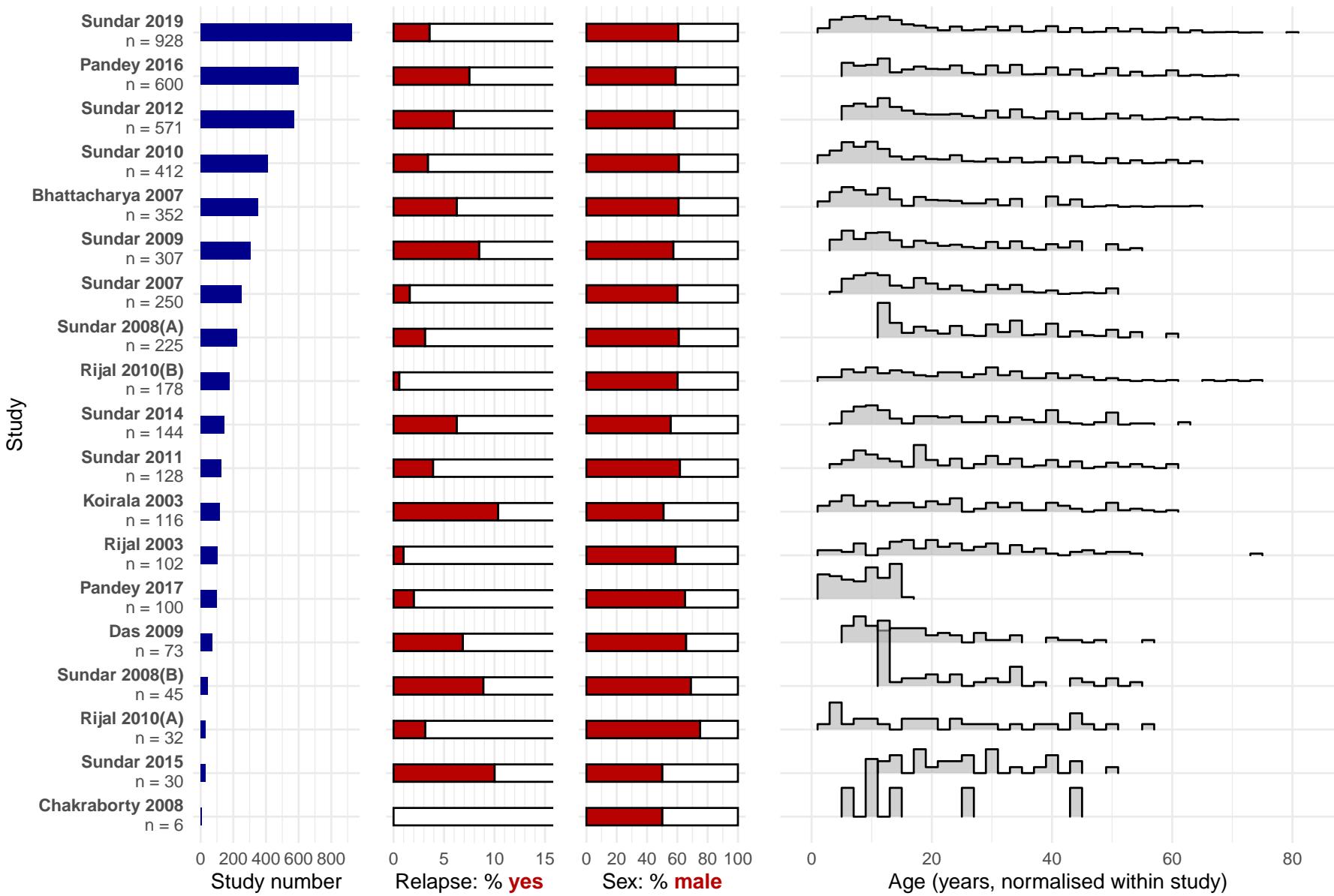


Figure 5.3: Graphical summary of the Indian subcontinent study-specific sample sizes and distributions of relapse status, sex, and age.

Categorical variables

Across all studies, 2,745 (59.7%) of patients were male, ranging from 50.0% to 75.0% at the study level.

Relapse within 6 months was identified in 228 (5.0%) patients, varying from 0% to 10.4% at the study level.

The majority of patients (52.4%) had mild/normal malnutrition according to the definition provided in Section 4.3.2. Moderate and severe malnutrition affected 28.7% and 18.9% of patients overall, although these proportions varied significantly across studies and were affected by considerable missing data (see Appendix Figure C.1).

Approximately half of all patients (49.8%) had severe anaemia at the time of recruitment.

At the patient level, the most common treatment regimen was 28 days of oral miltefosine (35.6%), followed by 10mg/kg single dose liposomal amphotericin B (28.9%). The remaining treatment regimens (35.4% of patients), consisted of a broad range of experimental and non-experimental regimens, including amphotericin B deoxycholate, other (not Gilead) lipid formulations of amphotericin B, paromomycin, SSG, pentamidine, and human placenta extract (Figure 5.2).

The most common baseline parasite grade on tissue aspirate was 1+ (40.7% of patients), while the median grade was 2+ (25.9% of patients at this grade; IQR: 1 to 3). The proportion of patients decreased with increasing parasite grade, with 54 patients (1.8%) exhibiting a grade of 5+. Where reported, 92.0% of tissue aspirates were obtained from the spleen. The remaining aspirates, were from bone marrow and accounted for almost all aspirates performed in three studies from Nepal[226, 227, 229] (Appendix Figure C.1).

Continuous variables

The median age was 18 years, ranging from 1 to 80 years (IQR: 10 to 32 years). Overall the distribution was right-skewed, with study-specific distributions reflecting age-specific inclusion criteria. 138 (3.0%) of patients were under 5 years, and 47 (1.0%) were 65 years or over.

In adults (≥ 19 years) the median BMI was 18.2 kg/m^2 (IQR: 16.4 to 20.8) (1,313 patients). In children (≥ 5 and < 19 years), the median BMI-for-age z-score was -1.68 (IQR: -2.67 to -0.72) (1,338 patients), and in infants (< 5 years) the median weight-for-height z-score was -1.80 (IQR: -2.97 to -0.99) (27 patients).

The median spleen size was 4cm (IQR: 2 to 7cm), and ranged from 0 to 22cm. Eight studies reported patients without splenomegaly at baseline[63, 66, 70, 92, 218, 219, 221, 222], corresponding to 5.5% of patients with recorded spleen sizes.

Variable	Overall (%) n = 4,599	Final cure (%) n = 4,371	Relapse (%) n = 228
Sex			
Female	1,854 (40.3)	1,771 (40.5)	83 (36.4)
Male	2,745 (59.7)	2,600 (59.5)	145 (63.6)
Malnutrition			
Normal/mild	1,403 (30.5)	1,333 (30.5)	70 (30.7)
Moderate	769 (16.7)	732 (16.7)	37 (16.2)
Severe	506 (11.0)	485 (11.1)	21 (9.2)
(Missing)	1,921 (41.8)	1,821 (41.7)	100 (43.9)
Anaemia			
Non-severe	2,089 (45.4)	1,973 (45.1)	116 (50.9)
Severe	2,071 (45.0)	1,985 (45.4)	86 (37.7)
(Missing)	439 (9.5)	413 (9.4)	26 (11.4)
Treatment			
Miltefosine ¹	1,639 (35.6)	1,526 (34.9)	113 (49.6)
Other	1,629 (35.4)	1,562 (35.7)	67 (29.4)
LAMB ²	1,331 (28.9)	1,283 (29.4)	48 (21.1)
Parasite grade			
1+	1,201 (26.1)	1,152 (26.4)	49 (21.5)
2+	764 (16.6)	733 (16.8)	31 (13.6)
3+	610 (13.3)	567 (13.0)	43 (18.9)
4+	323 (7.0)	301 (6.9)	22 (9.6)
5+	54 (1.2)	53 (1.2)	1 (0.4)
(Missing)	1,647 (35.8)	1,565 (35.8)	82 (36.0)
Aspirate source³			
Bone	235 (8.0)	221 (7.9)	14 (9.5)
Spleen	2,717 (92.0)	2,585 (92.1)	132 (90.4)

¹ 28 days of linear-dosed miltefosine at standard dosing.

² Single dose liposomal amphotericin B (Gilead) 10mg/kg.

³ Denominator for % in aspirate source: number of patients with documented parasite grade (overall: 2,952; final cure: 2,806; relapse: 146; no missing data).

Table 5.2: Summary of categorical candidate predictors and parasite source across contributed studies from the Indian subcontinent. Missing data are described where present. SDA: Single dose liposomal amphotericin B 10mg/kg.

The median duration of fever prior to patient recruitment was exactly 30 days (IQR: 20 to 60 days). The distribution was markedly right-skewed, ranging from 1 to 730 days.

For distributions of laboratory results (haemoglobin, white blood cells, platelets, creatinine, and alanine aminotransferase) please refer to Table 5.3 and Figure 5.5.

Variable	Overall (n = 4,599)		Final cure (n = 4,371)		Relapse (n = 228)	
	Median (IQR)	Missing ¹ (%)	Median (IQR)	Missing (%)	Median (IQR)	Missing ¹ (%)
Age (years)	18 (10 – 32)	7 (0.2)	18 (10 – 33)	6 (0.1)	14 (8 – 32)	1 (0.4)
Height (cm)	150.0 (125.0 – 161.5)	1,914 (41.6)	150.0 (126.0 – 161.0)	1,815 (41.5)	149.4 (124.0 – 164.6)	99 (43.4)
Weight (kg)	37 (21 – 46)	418 (9.1)	36.8 (21 – 46)	389 (8.9)	35 (19 – 49)	29 (12.7)
BMI (kg/m^2) ²	18.22 (16.37 – 20.81)	841 (39.0)	18.17 (16.33 – 20.70)	804 (39.1)	19.77 (17.24 – 24.07)	37 (38.1)
BMI-FA z-score ³	-1.68 (-2.67 – -0.72)	962 (41.8)	-1.67 (-2.65 – -0.71)	903 (41.5)	-1.99 (-2.81 – -1.11)	59 (47.6)
WFH z-score ⁴	-1.80 (-2.97 – -0.99)	111 (80.4)	-1.53 (-2.51 – -0.97)	108 (81.8)	-2.73 (-3.13 – -2.27)	3 (50.0)
Spleen size (cm)	4 (2 – 7)	642 (14.0)	4 (2 – 7)	595 (13.6)	3 (2 – 6)	47 (20.6)
Fever duration (days)	30 (20 – 60)	1,779 (38.7)	30 (20 – 60)	1,667 (38.1)	20 (15 – 30)	112 (49.1)
Parasite grade	2 (1 – 3)	1,647 (35.8)	2 (1 – 3)	1,565 (35.8)	2 (1 – 3)	82 (36.0)
WBC ($\times 10^9/\text{L}$)	3.4 (2.5 – 4.5)	435 (9.5)	3.4 (2.4 – 4.5)	409 (9.4)	3.4 (2.7 – 4.5)	26 (11.4)
Platelets ($\times 10^9/\text{L}$)	112 (77 – 155)	434 (9.4)	112 (77 – 155)	408 (9.3)	119.5 (83 – 160)	26 (11.4)
Haemoglobin (g/L)	79 (67 – 93)	433 (9.4)	79 (67 – 92)	407 (9.3)	82.5 (69 – 96)	26 (11.4)
ALT (IU/L)	31 (20 – 52)	449 (9.8)	31.2 (20 – 52)	421 (9.6)	30 (19 – 52)	28 (12.3)
Creatinine ($\mu\text{mol}/\text{L}$)	63.7 (51.3 – 79.6)	646 (14.0)	63.7 (51.3 – 79.6)	598 (13.7)	63.7 (51.3 – 76.0)	48 (21.1)

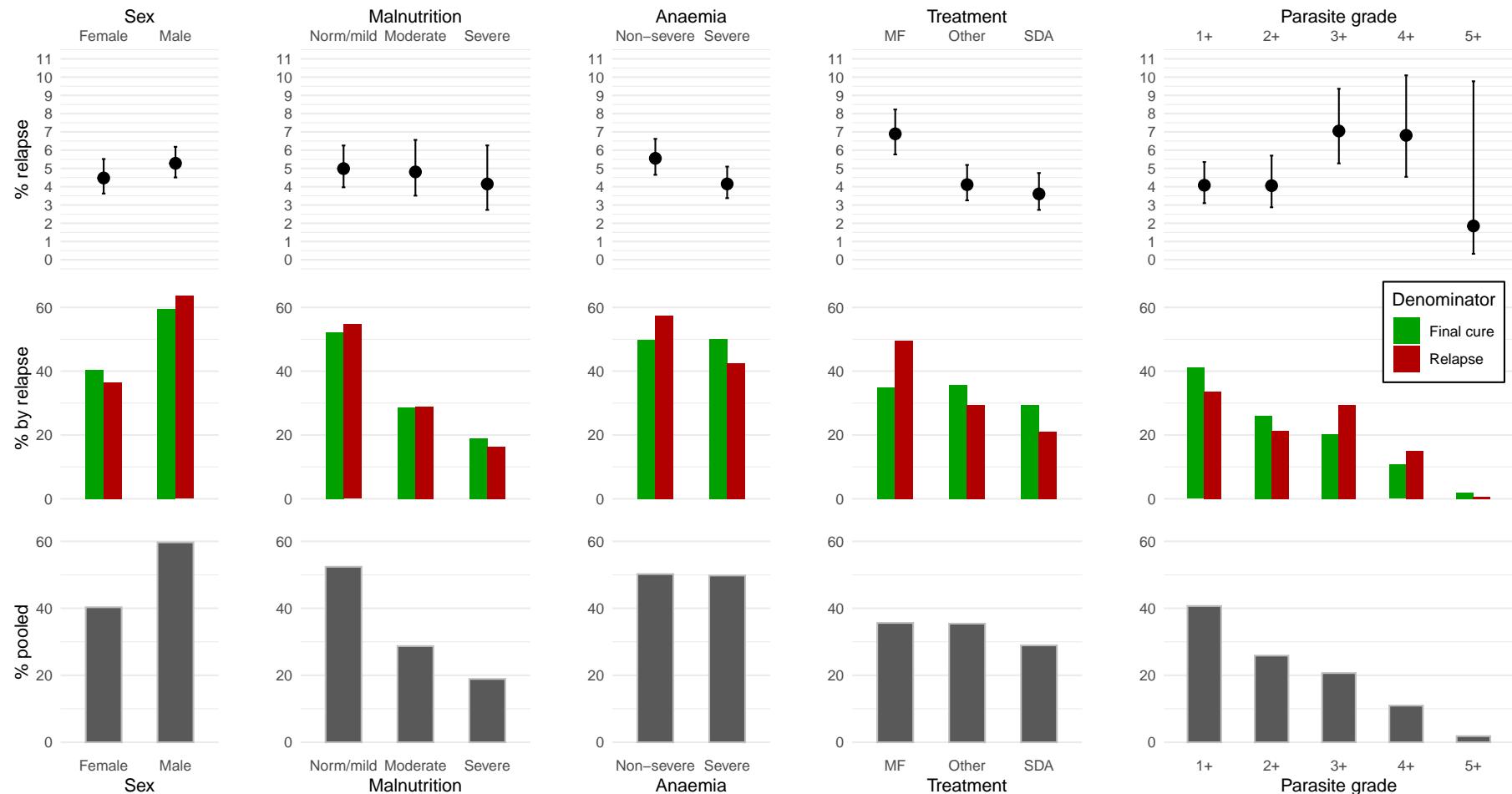
¹ Denominator for missing %: total number of patients in respective group (overall, relapse or final cure). For measures of malnutrition (BMI, BMI-for-age z-score, and weight-for-height z-score), see below.

² Denominator for missing %: number of patients aged ≥ 19 years, n = 2,154 (relapse: 97, final cure: 2,057).

³ Denominator for missing %: number of patients aged 5–18 year inclusive, n = 2,300 (relapse: 124, final cure: 2,176).

⁴ Denominator for missing %: number of patients aged < 5 years, n = 138 (relapse: 6, final cure: 132).

Table 5.3: Summary of continuous candidate predictors across contributed studies from the Indian subcontinent. Including additional variables used for the derivation of malnutrition status (height, weight, BMI, BMI-for-age z-score, weight-for-height z-score). ALT: alanine aminotransferase; BMI(-FA): body mass index(-for age); cm: centimetres; IQR: inter-quartile range, IU: international units; kg: kilograms; L: litres; m: metres; WBC: white blood cells; WFH: weight-for-height; g: grams; μmol : micromoles.



5.1.3 Pooled Univariable Associations

Unadjusted relationships between variables (including all candidate predictors, excluding missing data) and relapse risk are presented in tabular form (Tables 5.2, 5.3) and visually alongside their distributions (Figure 5.4 for categorical variables, and Figures 5.6 and 5.5 for continuous non-laboratory and laboratory variables, respectively). The relationships are presented on the log-odds (logistic) scale for continuous candidate predictors in Appendix Figure C.17.

Across continuous candidate predictors, GAM smooths suggested often non-linear relationships with relapse risk, with wider uncertainty at the extremes of the predictor distributions where data were sparse. Apparent trends were most evident for age, duration of fever and spleen size. Age showed a shallow U-shaped pattern, reaching a minimum relapse risk at approximately 20 years, while duration of fever showed a marked downward trend, with longer fever durations associated with lower relapse risk. With spleen size, a notable downward trend in risk was seen for spleen sizes over 2cm, perhaps better appreciated on the logit-log scale in Appendix Figure C.17. For the laboratory predictors, weak upward trending monotonic patterns were observed for white blood cells and platelets, with higher values associated with increased relapse risk.

Trends in non-candidate predictors, including weight, height, and haemoglobin, were also apparent. A marked upward trend was seen with haemoglobin and relapse risk, which was also evidence in the categorical associations, with severe anaemia associated with a lower relapse risk compared to non-severe anaemia.

Treatment with miltefosine was associated with a higher unadjusted relapse risk when compared with 10mg/kg single-dose liposomal amphotericin B or ‘Other’ treatment.

Patients with parasite grades of 3+ and 4+ were associated with higher relapse risk compared to patients with grades 1+ and 2+. Extrapolation of any trend to patients with 5+ parasite grade was limited by small numbers.

A correlation matrix showing associations between continuous variables is presented in Appendix Figure C.15, and between continuous and categorical variables in Appendix Figure C.16. Inter-predictor correlations are considered further in the Discussion section.

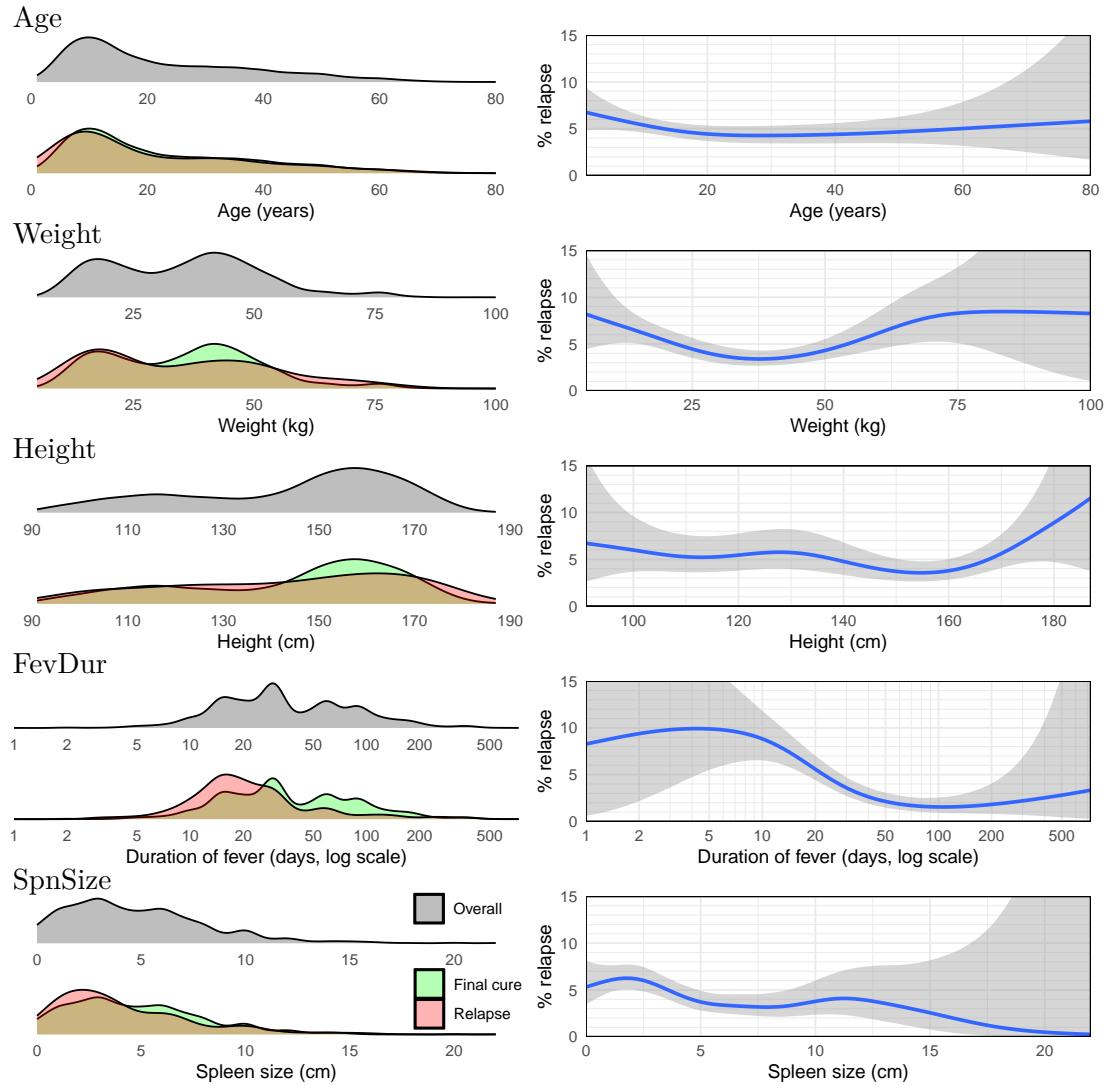


Figure 5.5: Distributions and predictor-outcome relationships for continuous non-laboratory candidate predictors. FevDur: duration of fever; SpnSize: spleen size. For each candidate predictor, left upper panel shows the overall density pooled across studies and the left lower panel shows overlapping densities normalised by relapse status. The right panel shows a univariable generalised additive model spline fit, with 95% confidence interval, of relapse.

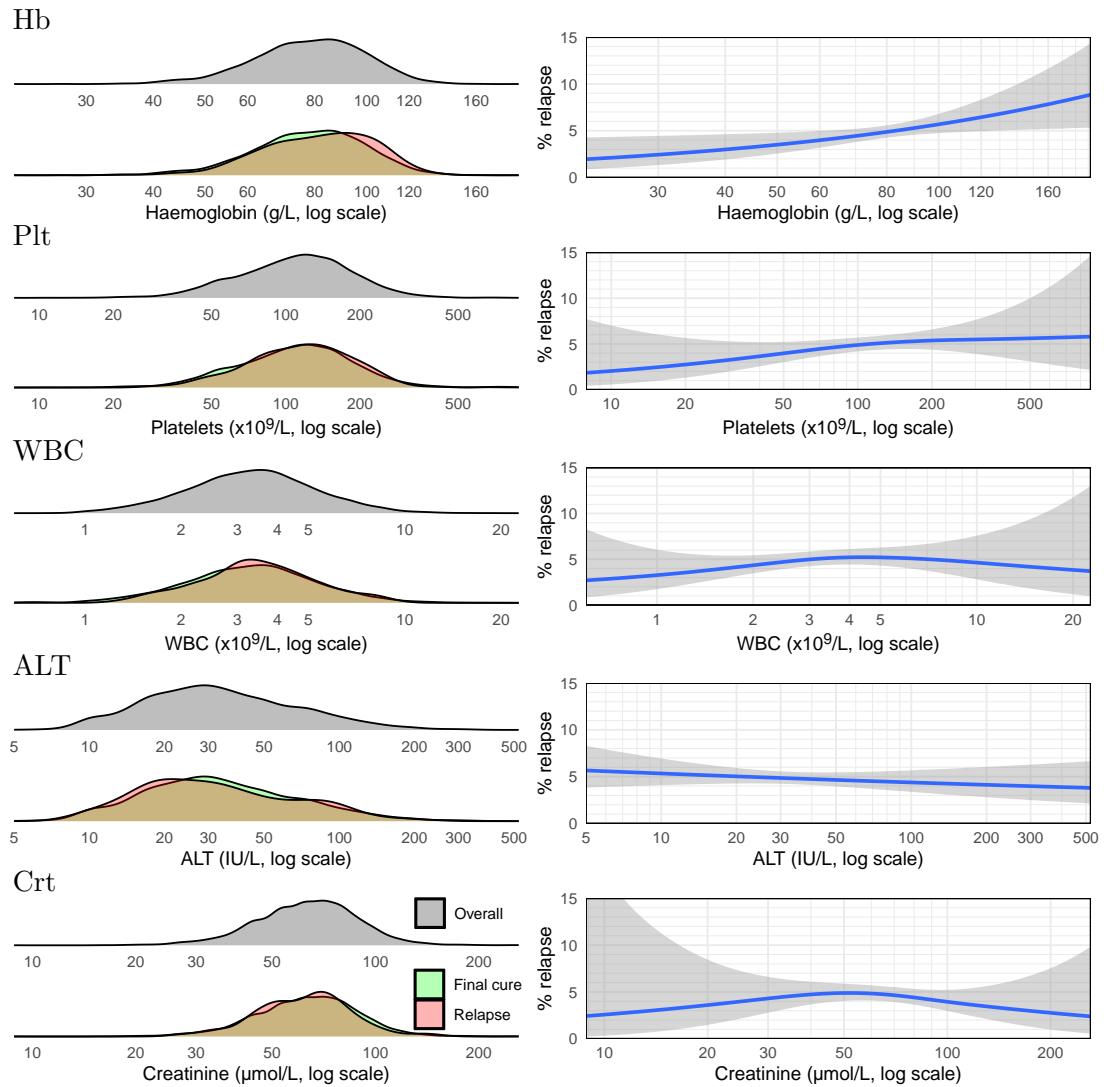


Figure 5.6: Pooled distributions and predictor-outcome relationships for continuous laboratory candidate predictors. All predictors presented on log scale. Hb: haemoglobin; Plt: platelet; WBC: white blood cells; ALT: alanine aminotransferase; Crt: creatinine. For each candidate predictor, left upper panel shows the overall density pooled across studies and the left lower panel shows overlapping densities normalised by relapse status. The right panel shows a univariable generalised additive model spline fit, with 95% confidence interval, of relapse.

5.1.4 Missing Data

Missing data were frequent among the candidate predictors, with 3,697 (80.4%) of patients missing at least one candidate predictor data point. Just under half of all patients (2,177 [47.3%] patients) were missing exactly one data point, and 1,520 (33.1%) patients were missing two or more data points. No missing data were present in the outcome (relapse) or random-effect (study) variables.

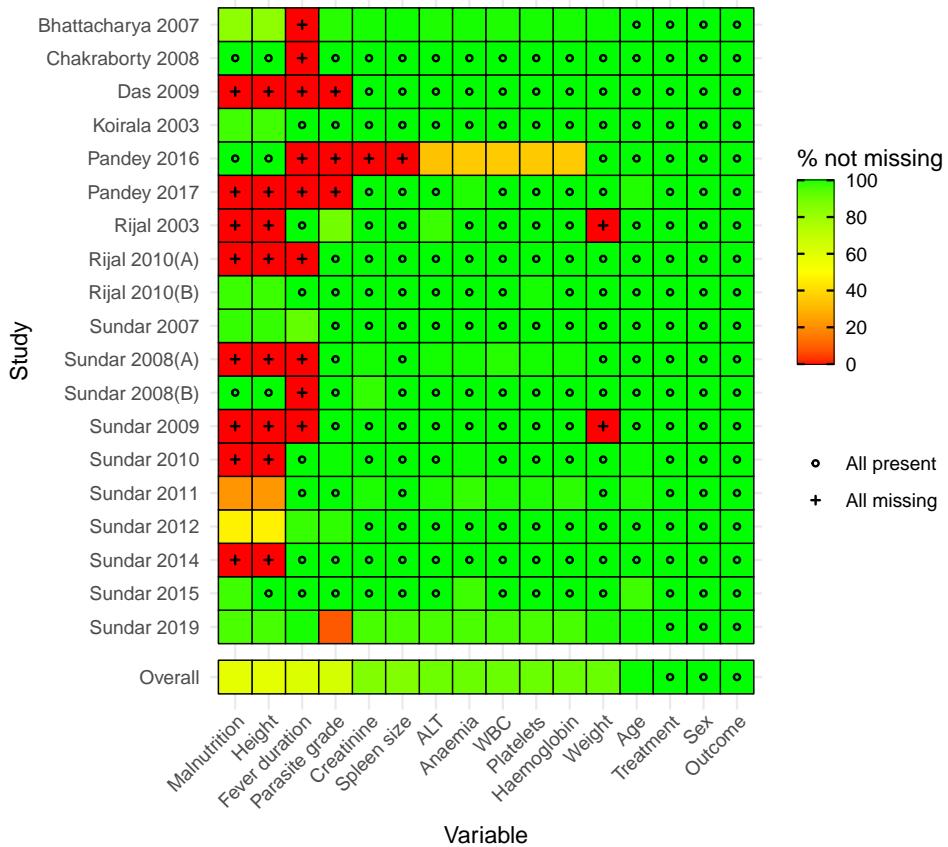


Figure 5.7: Density plot illustrating the amount of missing data overall and across contributing studies from the Indian subcontinent. Study ordered by lead author and year of publication (or protocol). Variables ordered by amount of missingness. ALT: alanine aminotransferase; WBC: white blood cells.

The candidate predictor with the most missingness was malnutrition, which affected 1,921 (41.8%) patients due to a lack of height information. After malnutrition, fever duration was missing in 1,779 (38.7%) of patients, and parasite grade was missing in 1,647 (35.8%) patients. Remaining predictors had under 15% missingness. Missingness patterns, ordered by missingness in the candidate predictors, are presented in Figure 5.7 at the study level and overall.

On review of the missing data diagnostic plots (as described in Section 4.3.4 and available for review in the [Supplementary Material](#)), no clear or consistent patterns indicating violations of the missing-at-random assumption, were apparent. Convergence was obtained well before the 20 iterations for the majority of imputed predictors, and the distributional assumptions of the imputation model appeared robust on inspection of the diagnostic density and scatter plots.

5.2 Model Results

Model Specification and Coefficient Estimates

Forest plots of the final model predictors are presented in Figure 5.8. Full specification of the final models, including intercept terms, p-values, and predictor transformations, are presented in Appendix Tables C.1 and C.2.

For both models, final predictors included: age (both linear and quadratic terms), duration of fever, treatment regimen, and presence of severe anaemia. Parasite grade was also included when considered as a candidate predictor. As can be appreciated from Figure 5.8, the adjusted odds ratios were similar across the two models. The similarity between models can also be appreciated in Figure 5.9, which shows relapse probability predictions with the model intercept recalibrated to the Sundar 2019 dataset[92].

In both models, U-shaped relationships between age and relapse risk were shown, reflecting a significant positive age² (quadratic) coefficient. Inverse relationships between fever duration and relapse risk were also demonstrated. In the model including parasite grade, the relapse odds decreased by 34.8% (95% CI: 24.0–44.1%) for each doubling of fever duration, with similar findings with the model excluding parasite grade. When included, a unit increase in parasite grade (e.g. from 1+ to 2+) was associated with a 30.6% increase in relapse odds (95% CI: 12.1–52.2%). Relapse odds in the 10mg/kg single dose liposomal amphotericin B, or ‘Other’ treatment groups were significantly less (approximately half) than the odds in the standard dose miltefosine regimen, although with marked uncertainty. The presence of severe anaemia was also found to be associated with decreased odds of relapse by approximately 25% (25.3%, 95% CI: 44.4–0.2% in the model including parasite grade). Appendix Tables C.1 and C.2 provide the complete predictor coefficients and standard errors for both models.

Pooled estimates of intraclass correlation coefficients (ICC)² were 3.5% for the model including parasite grade, and 4.4% for the model excluding parasite grade.

²ICC quantifies the proportion of total variance in the latent propensity for the outcome attributable to between-study differences.

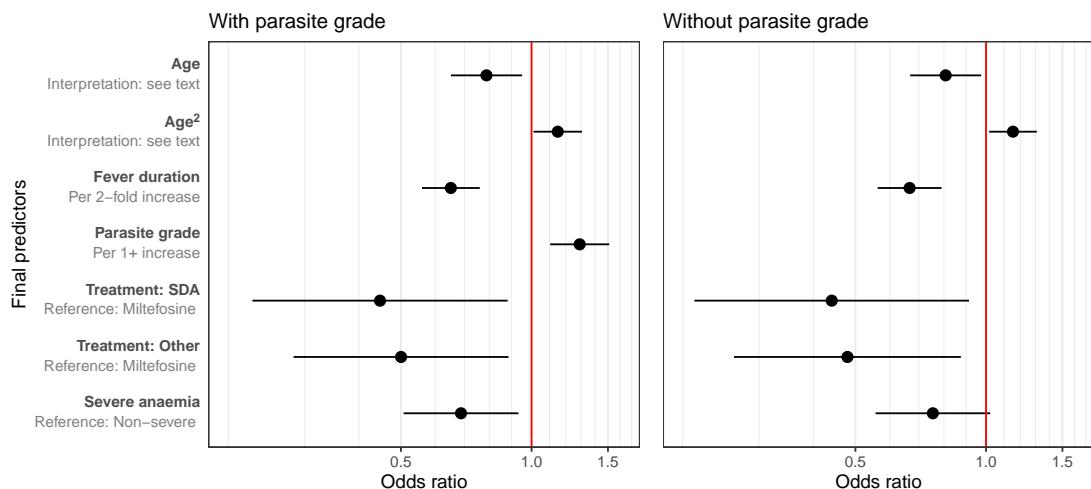
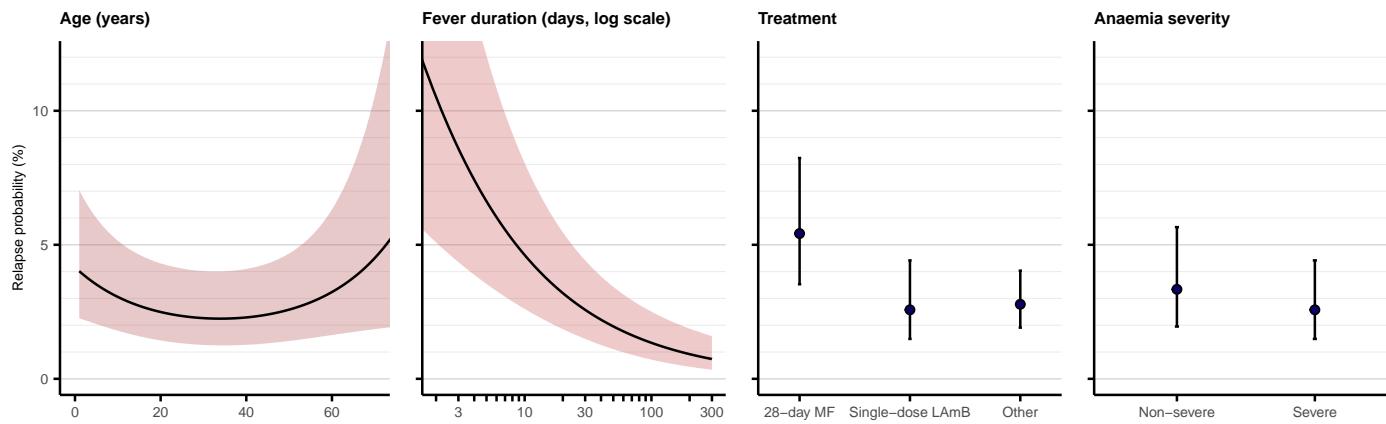


Figure 5.8: Forest plots of adjusted odds ratios with 95% confidence intervals for final model predictors. For age, the odds ratio represents a combination of linear and quadratic effects, with age centred by the mean and scaled by the standard deviation. Please refer to Figure 5.9 for the adjusted relapse probabilities after model intercept recalibration to the observed relapse rate in the Sundar 2019 dataset[92].

ISC model: without parasite grade



ISC model: with parasite grade

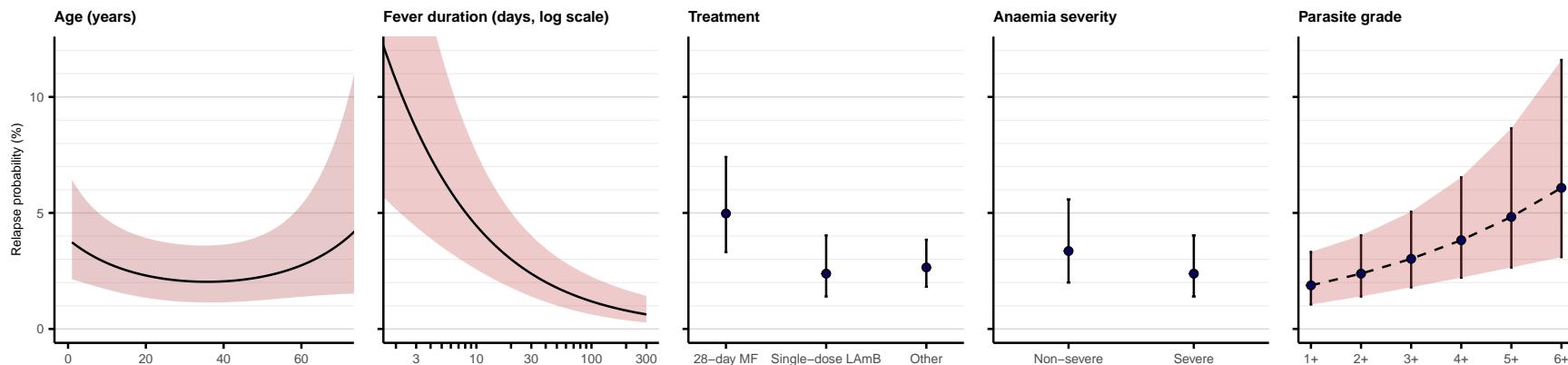


Figure 5.9: Adjusted associations between final predictors and predicted relapse probability, as estimated from the final ISC prognostic models. Probabilities were calculated from optimism-adjusted models and following logistic recalibration (intercept-term only) to data contributed from Sundar 2019[92]. Where not varying in the plot, predictions are standardised to a representative reference participant: median age (18 years), median fever duration (30 days), treated with 10mg/kg single-dose liposomal amphotericin B, with severe anaemia, and — for the model including parasite grade — a median parasite count of 2+.

Model Performance and Internal Validation

Apparent and optimism-adjusted c-statistics and calibration slopes are presented in Table 5.4. When assessed in studies with >5 relapse events, model discrimination was estimated at 0.70 (95% CI: 0.66–0.74) in the model including parasite grade, and 0.69 (95% CI: 0.64–0.74) in the model excluding parasite grade. These estimates reduced to 0.68 and 0.67, respectively, after adjusting for optimism. No evidence of significant between-study heterogeneity was identified in either model, with forest plots presented in Figure 5.10 (model including parasite grade) and Appendix Figure C.18 (excluding parasite grade).

	Estimate (95% CI)	Average optimism	Optimism-adjusted performance
Model: with PG			
C-statistic	0.70 (0.66–0.74)	0.014	0.68
Calibration slope	1.01 (0.69–1.32)	0.093	0.91
Model: without PG			
C-statistic	0.69 (0.64–0.74)	0.016	0.67
Calibration slope	1.02 (0.68–1.35)	0.098	0.92

Table 5.4: Apparent and optimism-adjusted performance measures. Abbreviations: CI: confidence interval; PG: parasite grade

Optimism in calibration slopes were estimated at 0.093 and 0.098 in the models including and excluding parasite grade, respectively. Resulting uniform shrinkage factors were 0.91 and 0.92, respectively. Multiplying together these shrinkage factors with the estimated model coefficients will result in the optimism-adjusted coefficients (Appendix Tables C.1 and C.2). No significant evidence of between-study heterogeneity in calibration slope was identified, with forest plots presented in Figure 5.11 (model including parasite grade) and Appendix Figure C.19 (model excluding parasite grade).

Visual inspection of the calibration plots comparing predicted and observed relapse probabilities showed minimal deviation from perfect calibration (Figure 5.12). Calibration plots showing predicted and observed relapse probabilities for fever duration (Figure 5.13 for model including parasite grade), and other predictors (Appendix Figures C.20 to C.24 for model including parasite grade and C.25 to C.28 excluding parasite grade) and also showed good overall agreement, with predicted relapse probabilities lying within the 95% confidence intervals of the observed probabilities.

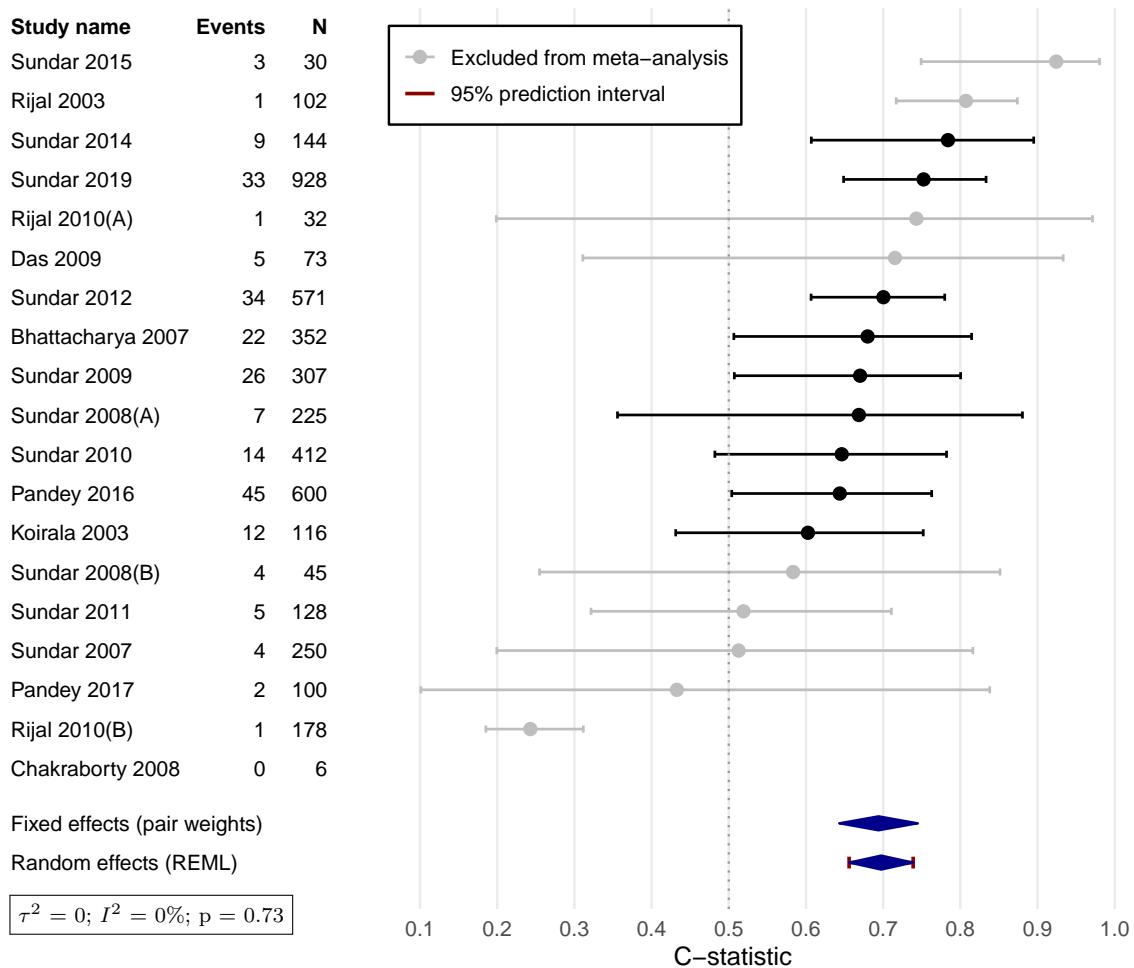


Figure 5.10: Forest plot showing individual and pooled study c-statistics, for the model **including** parasite grade. For the model excluding parasite grade refer to Appendix C.18. Pooled c-statistics are presented from both fixed-effects and random-effects meta-analysis models, after excluding studies with ≤ 5 relapse events. Blue diamonds: pooled summary estimates with 95% confidence intervals. For Chakraborty 2008, no relapse events occurred and c-statistic is therefore undefined.

Calibration intercepts (calibration-in-the-large) were found to vary significantly between studies for both models, as can be appreciated from the forest plots in Figure 5.11 for the model including parasite grade, and Appendix Figure C.19 for the model excluding parasite grade (test for heterogeneity; $p = 0.01$ and $p = 0.002$ for models including and excluding parasite grade).

The distribution of the final predictors selected across the 2×500 bootstrap models are presented in Appendix Table C.3. Reassuringly, the most frequently selected predictors correspond to the final predictors selected in both final models. However, a degree of instability is apparent, with predictors such as spleen size, sex, alanine aminotransferase, and the cubic age term being selected in 100–250 bootstraps.

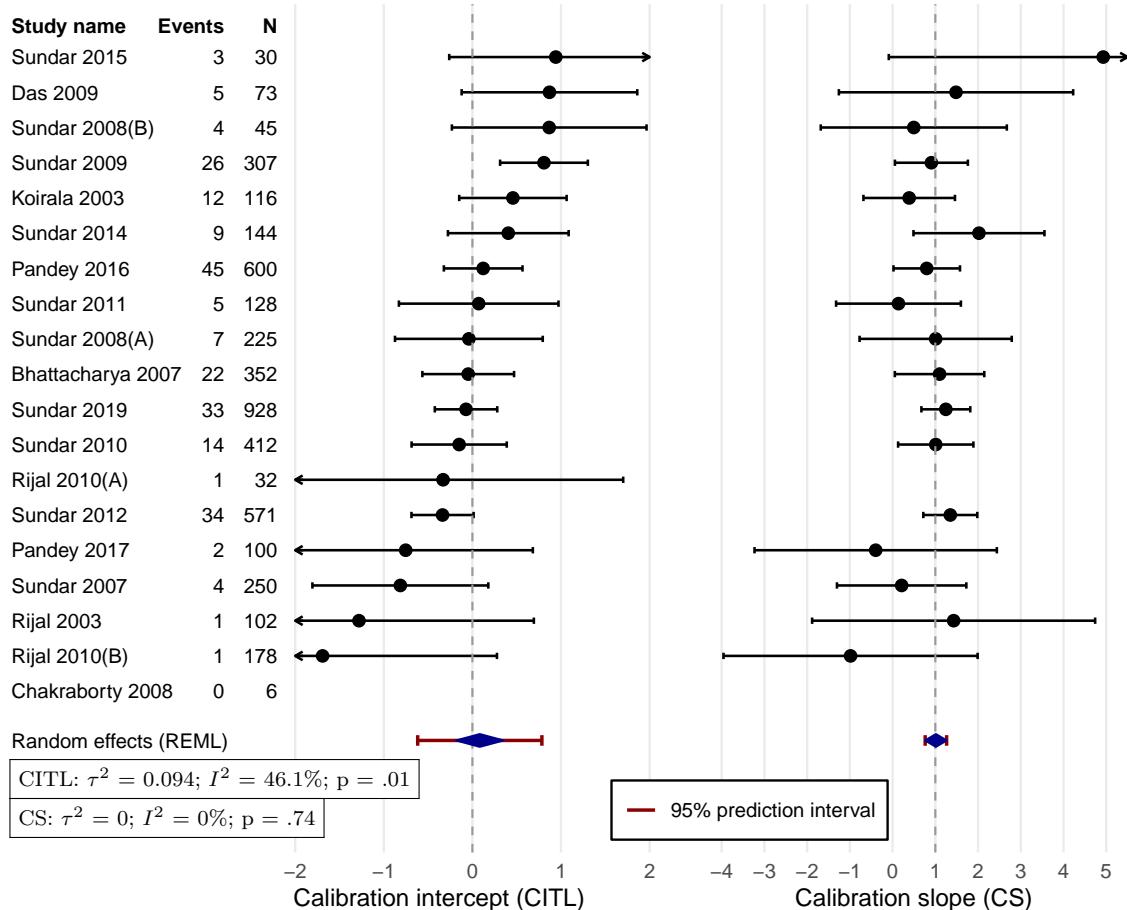


Figure 5.11: Forest plots showing individual and pooled study calibration measures for the model **including** parasite grade. Left: calibration intercept (calibration-in-the-large, CITL); Right: calibration slope (CS). Blue diamonds: summary estimates with 95% confidence intervals. Calibration measures not presented for Chakraborty 2008 due to no relapse events. Calibration slope not presented for Rijal 2010(A) due to only one relapse event and few total participants leading to failure of model convergence.

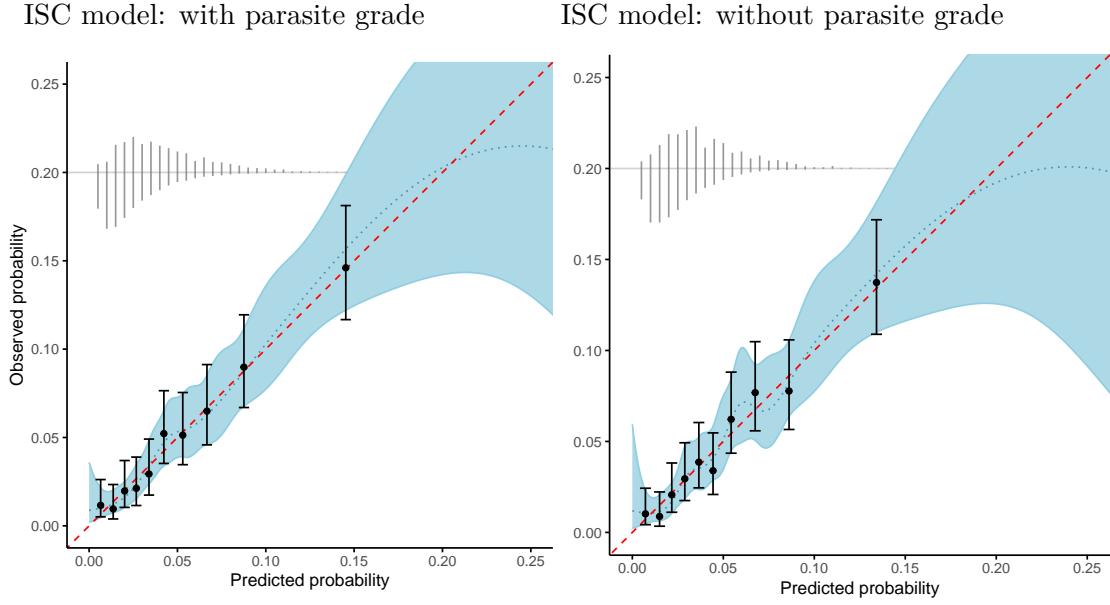


Figure 5.12: Calibration plots showing observed versus predicted probabilities for deciles of predicted probability. Red dashed line represents perfect calibration. Observed probabilities are presented with 95% confidence intervals (black error bars). A generalised additive model is fitted to show the smoothed mean observed probability (blue dotted line) with 95% confidence intervals (blue ribbon). Histograms, normalised by outcome, are overlaid to illustrate the distribution of relapses and cures across the expected probabilities.

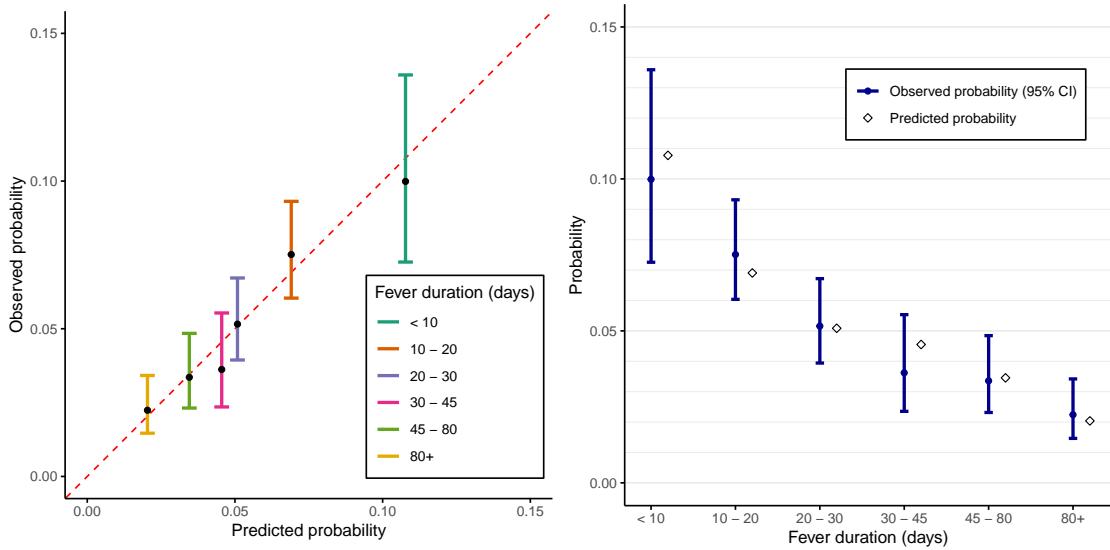


Figure 5.13: Calibration plots for different fever durations (model including parasite grade).

6

Results: East Africa Models

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6.1 Descriptive Analysis

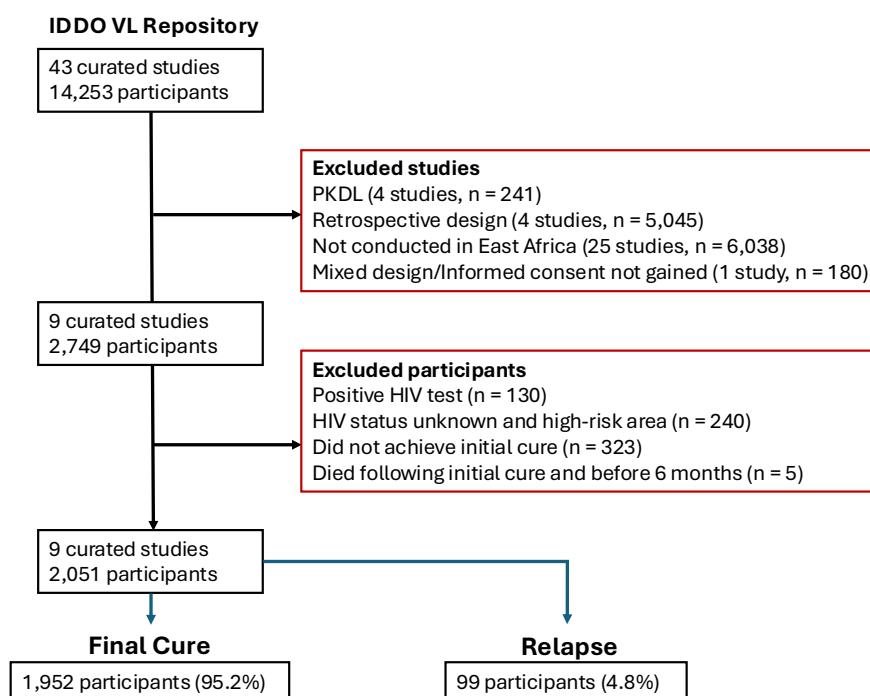


Figure 6.1: Flow diagram showing the studies and participants excluded from East Africa model development, following application of the eligibility criteria. HIV: human immunodeficiency virus; IDDO: Infectious Diseases Data Observatory; EA: East Africa; PKDL: post kala-azar dermal leishmaniasis; VL: visceral leishmaniasis.

Table 6.1: Key characteristics of included studies from East Africa, ordered by lead author and year of publication/protocol. -: not reported; BD: twice daily (bis die); D: Day(s); IM: intramuscular; IV: intravenous; LAMB: Liposomal amphotericin B (Gilead formulation); MF: Miltefosine; mg/kg: milligrams per kilogram; OD: once daily (omni die); PO: per os (oral); PM: Paromomycin; SSG: Sodium stibogluconate;

Study ¹	Title	Journal	Sponsor/ funding	Location(s)	Study design	Study arm(s) ⁴	Age (years)	Study period	n (model)	Relapses (%)
Hailu 2010[119]	Geographical variation in the response of visceral leishmaniasis to paromomycin in East Africa: a multicentre, open-label, randomized trial	PLoS Negl Trop Dis	DNDi/MSF	5 centres: Ethiopia (Gondar University Hospital, Arba Minch Hospital); Sudan (MSF Treatment Centre, Um el Khjer; Ministry of Health Hospital, Kassab); Kenya (CCR, KEMRI, Nairobi)	Multicentre, open-label, randomised trial	(1) SSG, 20mg/kg, IV or IM, OD, 30D; (2) PM, 15mg/kg, IM, OD, 21D; (3) Combination of PM and SSG, same dose, frequency and route, 17D	4–60	2004–2008	289	21 (7.3)
Khalil 2014[117]	Safety and efficacy of single dose versus multiple doses of AmBisome for treatment of visceral leishmaniasis in eastern Africa: a randomised trial	PLoS Negl Trop Dis	DNDi (multiple funders)	3 centres: Ethiopia (Gondar University Hospital, Arba Minch Hospital); Sudan (Ministry of Health Hospital, Kassab)	Multicentre, open-label, non-inferiority, randomised trial with adaptive design	LAMB, IV, either single dose at (1) 7.5mg/kg; (2) 10mg/kg; (3) 12.5mg/kg; (4) 15mg/kg, or multiple dose at (5) 3mg/kg, OD, D1-5, 14, 21 (total 21mg/kg)	≥4	2009–2011	92	11 (12.0)
Mbui 2019[122]	Pharmacokinetics, Safety, and Efficacy of an Allometric Miltefosine Regimen for the Treatment of Visceral Leishmaniasis in Eastern African Children: An Open-label, Phase II Clinical Trial	Clin Infect Dis	DNDi (multiple funders)	2 clinical sites: Kacheliba, West Pokot County, Kenya; Amudat, Karamoja sub-region, Uganda	Open-label, phase II, clinical trial	(1) MF, allometric dosing according to sex, height, and weight, BD, PO, 28D ²	4–12	2015–2016	29	2 (6.9)
Musa 2010[118]	Paromomycin for the treatment of visceral leishmaniasis in Sudan: a randomized, open-label, dose-finding study	PLoS Negl Trop Dis	DNDi (multiple funders)	Ministry of Health Hospital, Kassab, Sudan	Open-label, open-label, phase II, randomised, dose-finding study	(1) PM, 15mg/kg, IM, OD, 28D; (2) PM, 20mg/kg, IM, OD, 21D	4–60	2005–2006	40	8 (20.0)
Musa 2012[71]	Sodium stibogluconate (SSG) & paromomycin combination compared to SSG for visceral leishmaniasis in East Africa: a randomised controlled trial	PLoS Negl Trop Dis	DNDi/MSF (multiple funders)	6 centres: 5 centres described in Khalil 2014 (above) and Amudat Hospital, Uganda.	Multicentre, open-label, parallel-arm, randomised trial	(1) SSG, 20mg/kg, IV or IM, OD, 30D; (2) PM, 20mg/kg, IM, OD, 21D; (3) combination of SSG, 20mg/kg, IV or IM, OD, 17D and PM, 15mg/kg, IM, OD, 17D	4–60	2004–2010	638	30 (4.7%)
Ritmeijer 2001[239]	Ethiopian visceral leishmaniasis: generic and proprietary sodium stibogluconate are equivalent; HIV co-infected patients have a poor outcome	Trans R Soc Trop Med Hyg	MSF	Temporary MSF treatment centre, Densha, Ethiopia	Open-label, pseudo-randomised controlled trial	(1) SSG (generic) ³ , 20mg/kg, IM, 30D; (2) SSG (Pentostam, GlaxoWellcome), 20mg/kg, IM, 30D	all	1998–1999	112	1 (0.9)

continued on next page

Table 6.1: continued

Study ¹	Title	Journal	Sponsor/ funding	Location(s)	Study design	Study arm(s) ⁴	Age (years)	Study period	n (model)	Relapses (%)
Ritmeijer 2006[240]	A comparison of miltefosine and sodium stibogluconate for treatment of visceral leishmaniasis in an Ethiopian population with high prevalence of HIV infection	Clin Infect Dis	MSF	2 centres in Ethiopia: Humera Hospital, Mycadra Health Center	Open-label, randomised controlled trial	(1) SSG, 20mg/kg/day, IM, OD, 30D (extended if HIV positive); (2) MF, 100mg/day, PO, OD, 28D	≥15	2003–2005	248	6 (2.4)
Veeken 2000[241]	A randomized comparison of branded sodium stibogluconate and generic sodium stibogluconate for the treatment of visceral leishmaniasis under field conditions in Sudan	Trop Med Int Health	MSF	2 MSF treatment centres in Gedaref State, Sudan: Um Kuraa, Kassab	Open-label, pseudo-randomised controlled trial	(1) SSG (generic) ³ 20mg/kg, IM, 30D; (2) SSG (Pentostam, GlaxoWellcome), 20mg/kg, IM, 30D	all	1998–1999	465	4 (0.9)
Wasunna 2016[238]	Efficacy and Safety of AmBisome in Combination with Sodium Stibogluconate or Miltefosine and Miltefosine Monotherapy for African Visceral Leishmaniasis: Phase II Randomized Trial.	PLoS Negl Trop Dis	DNDi (multiple funders)	3 centres: Kenya (Kimale Health Centre); Sudan (Dooka Hospital and Ministry of Health Hospital, Kassab)	Phase II, open-label, non-comparative randomised trial (adaptive-sequential design)	(1) Combination of LAMB, 10mg/kg, IV, single dose, D1 and SSG, 20mg/kg, IM, OD, D2-11; (2) Combination of LAMB, 10mg/kg, IV, single dose, D1, and MF, 2.5mg/kg, PO, OD, D2-11; (3) MF ⁵ , 2.5mg/kg, PO, OD, 28D	7–60	2010–2012	138	16 (11.6)

¹ Study name is composed of the lead author and year of publication.

² Refer to the supplementary material of the publication for allometric dosing table[122].

³ SSG tested and dispensed by International Dispensary Association, The Netherlands; manufactured by Albert David Ltd, India.

⁴ For both arms in Veeken 2010, Ritmeijer 2001, and Ritmeijer 2006, if positive initial test-of-cure, treatment would continue with SSG, including if previously taking MF, until two subsequent consecutive tests of cure, performed weekly, were negative.

⁵ Actual dosing ranged from 2.0–3.33 mg/kg/day after rounding to nearest 10mg tablets; full regimen described in publication[238]

Variable	Overall (%) n = 2,051	Final cure (%) n = 1,952	Relapse (%) n = 99
Sex			
Female	532 (25.9)	503 (25.8)	29 (29.3)
Male	1,519 (74.1)	1,449 (74.2)	70 (70.7)
Malnutrition			
Normal/mild	735 (35.8)	710 (36.4)	25 (25.3)
Moderate	800 (39.0)	760 (38.9)	40 (40.4)
Severe	509 (24.8)	476 (24.4)	33 (33.3)
(Missing)	7 (0.3)	6 (0.3)	1 (1.0)
Anaemia			
Non-severe	1,049 (51.1)	1,015 (52.0)	34 (34.3)
Severe	999 (48.7)	934 (47.8)	65 (65.7)
(Missing)	3 (0.1)	3 (0.2)	0 (0.0)
Parasite grade			
1+	511 (24.9)	488 (25.0)	23 (23.2)
2+	237 (11.6)	219 (11.2)	18 (18.2)
3+	192 (9.4)	181 (9.3)	11 (11.1)
4+	179 (8.7)	169 (8.7)	10 (10.1)
5+	193 (9.4)	180 (9.2)	13 (13.1)
6+	77 (3.8)	60 (3.1)	17 (17.2)
(Missing)	662 (32.3)	655 (33.6)	7 (7.1)
Aspirate source¹			
Bone	131 (9.4)	110 (8.6)	21 (22.8)
Spleen	393 (28.3)	369 (28.9)	24 (26.1)
Lymph node	163 (11.7)	151 (11.8)	12 (13.0)
(Missing)	702 (50.5)	649 (50.7)	35 (38.0)

¹ Denominator for % in aspirate source: number of patients with documented parasite grade (overall: 1,389; final cure: 1,279; relapse: 92).

Table 6.2: Summary of categorical candidate predictors and parasite source across contributed studies from East Africa. Missing data are described where present.

Variable	Overall (n = 4,599)		Final cure (n = 4,371)		Relapse (n = 228)	
	Median (IQR)	Missing ¹ (%)	Median (IQR)	Missing (%)	Median (IQR)	Missing ¹ (%)
Age (years)	14 (9 – 22)	1 (0.0)	15 (9 – 22)	1 (0.1)	12 (9 – 20)	0 (0.0)
Height (cm)	153 (126 – 168)	9 (0.4)	154 (126 – 168)	8 (0.4)	143 (127 – 164)	1 (1.0)
Weight (kg)	35 (21 – 49)	1 (0.0)	35 (21 – 49)	1 (0.1)	28 (20.6 – 44.5)	0 (0.0)
BMI (kg/m^2) ²	17.56 (16.29 – 18.69)	4 (0.5)	17.54 (16.29 – 18.71)	3 (0.4)	17.63 (16.65 – 18.22)	1 (3.2)
BMI-FA z-score ³	-2.32 (-3.10 – -1.50)	2 (0.2)	-2.30 (-3.09 – -1.47)	2 (0.2)	-2.58 (-3.43 – -1.89)	0 (0.0)
WFH z-score ⁴	-2.36 (-3.12 – -1.58)	0 (0.0)	-2.32 (-3.01 – -1.55)	0 (0.0)	-3.42 (-3.89 – -3.24)	0 (0.0)
Spleen size (cm)	8 (5 – 11)	69 (3.4)	8 (5 – 11)	69 (3.5)	7 (4 – 10)	0 (0.0)
Fever duration (days)	40.4 (25.0 – 91.3)	349 (17.0)	40.4 (25.0 – 91.3)	320 (16.4)	30.4 (20.3 – 60.9)	29 (29.3)
Parasite grade	2 (1 – 4)	662 (32.3)	2 (1 – 4)	655 (33.6)	3 (2 – 5)	7 (7.1)
WBC ($\times 10^9/\text{L}$)	2.5 (1.8 – 3.5)	887 (43.2)	2.5 (1.8 – 3.5)	871 (44.6)	2.7 (1.8 – 3.6)	16 (16.2)
Platelets ($\times 10^9/\text{L}$)	106 (73 – 157)	890 (43.4)	105 (73 – 155)	874 (44.8)	110 (74.5 – 171)	16 (16.2)
Haemoglobin (g/L)	79 (67 – 91)	2 (0.1)	80 (67 – 92)	2 (0.1)	72 (62 – 83.5)	0 (0.0)
ALT (IU/L)	21 (14 – 31)	920 (44.9)	21 (14 – 31)	901 (46.2)	19 (14 – 30)	19 (19.2)
Creatinine ($\mu\text{mol}/\text{L}$)	44.2 (0.6 – 79.0)	826 (40.3)	44.2 (0.6 – 78.9)	815 (41.8)	44.2 (0.7 – 79.6)	11 (11.1)

¹ Denominator for missing %: total number of patients in respective group (overall, relapse or final cure). For measures of malnutrition (BMI, BMI-for-age z-score, and weight-for-height z-score), see below.

² Denominator for missing %: number of patients aged ≥ 19 years, n = 756 (relapse: 30, final cure: 726).

³ Denominator for missing %: number of patients aged 5–18 year inclusive, n = 1,165 (relapse: 65, final cure: 1,100).

⁴ Denominator for missing %: number of patients aged < 5 years, n = 129 (relapse: 4, final cure: 125).

Table 6.3: Summary of continuous candidate predictors across contributed studies from East Africa. Including additional variables used for the derivation of malnutrition status (height, weight, BMI, BMI-for-age z-score, weight-for-height z-score). ALT: alanine aminotransferase; BMI(-FA): body mass index(-for age); cm: centimetres; IQR: inter-quartile range, IU: international units; kg: kilograms; L: litres; m: metres; WBC: white blood cells; WFH: weight-for-height; g: grams; μmol : micromoles.

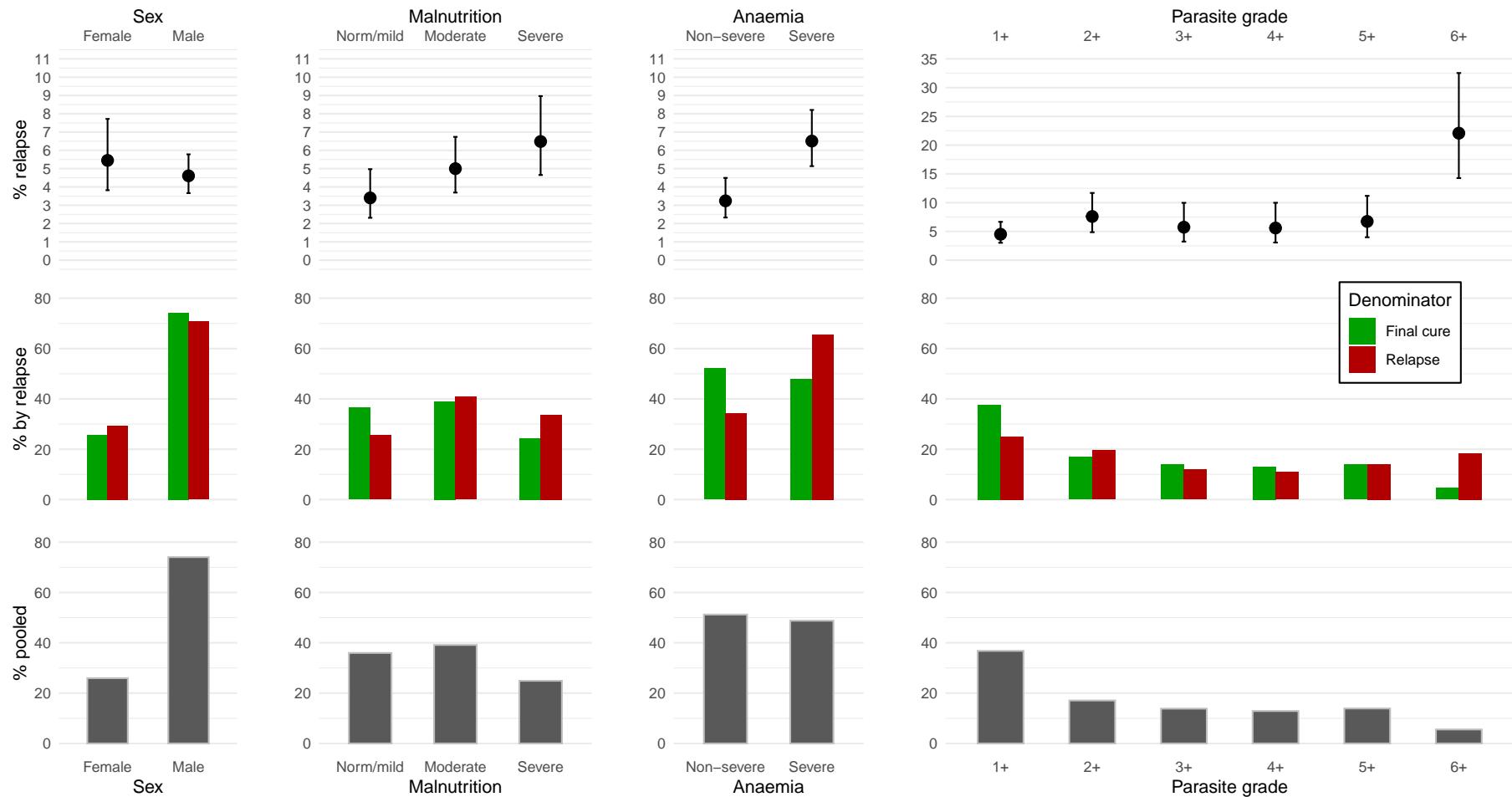


Figure 6.2: Pooled distributions and predictor-outcomes relationships for categorical candidate predictors. Excluding missing data. 95% binomial confidence intervals calculated using the Wilson method. Note: for parasite grade relapse %, y-axis is rescaled to accommodate increased risk in 6+ group. Norm: normal.

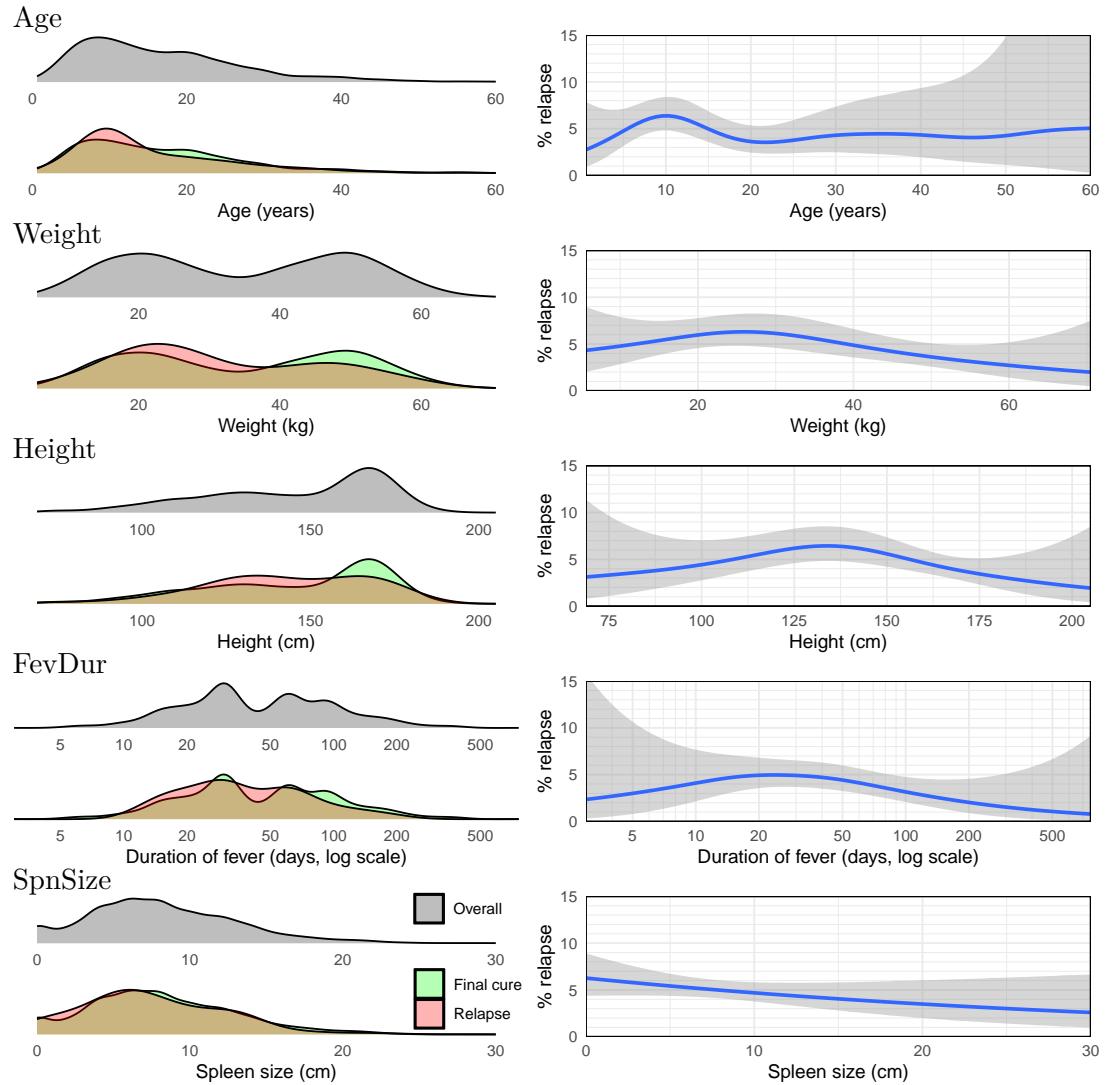


Figure 6.3: Distributions and predictor–outcome relationships for continuous non-laboratory candidate predictors. FevDur: duration of fever; SpnSize: spleen size. For each candidate predictor, left upper panel shows the overall density pooled across studies and the left lower panel shows overlapping densities normalised by relapse status. The right panel shows a univariable generalised additive model spline fit, with 95% confidence interval, of relapse.

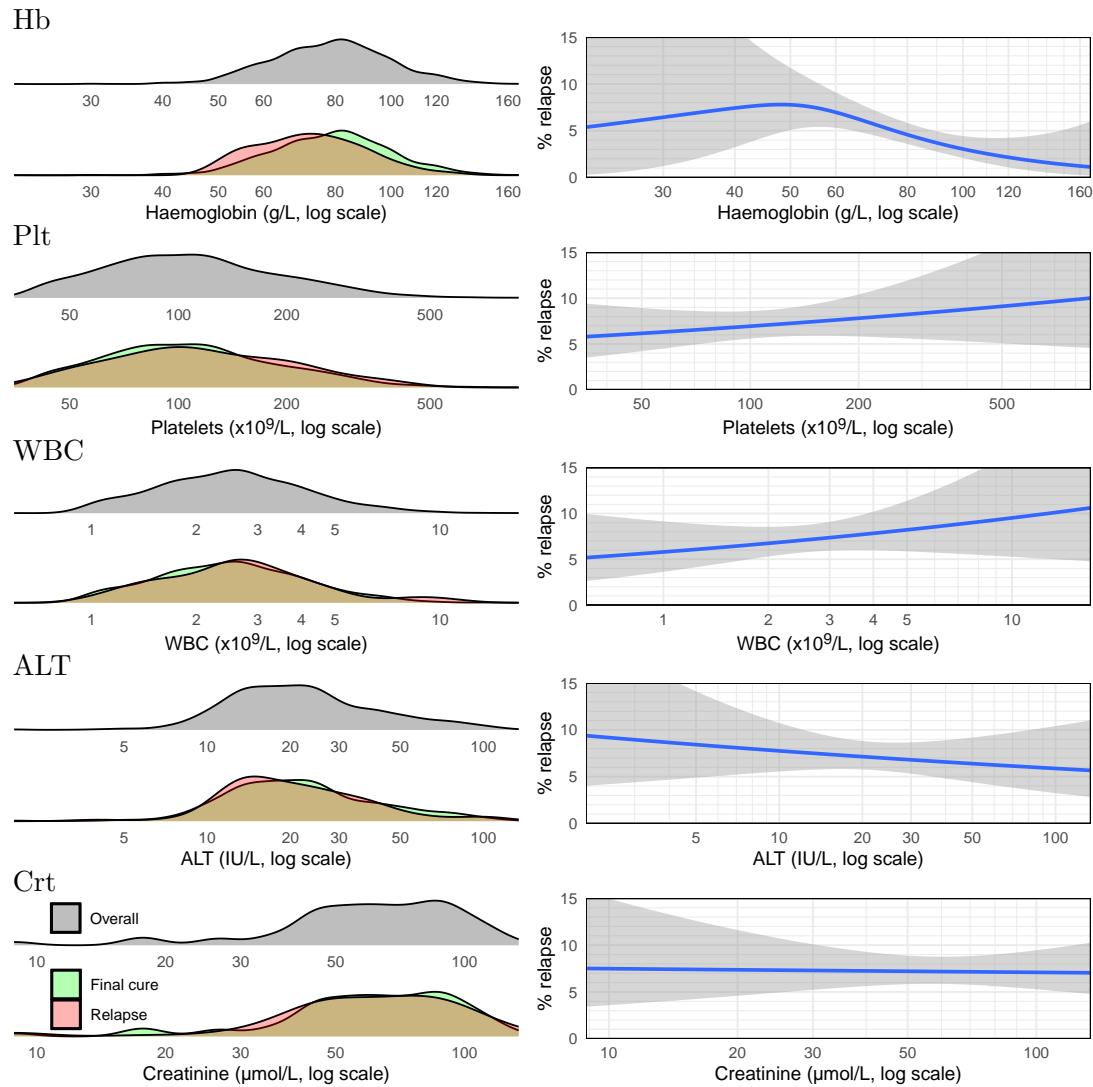


Figure 6.4: Pooled distributions and predictor–outcome relationships for continuous laboratory candidate predictors. All predictors presented on log scale. Hb: haemoglobin; Plt: platelet; WBC: white blood cells; ALT: alanine aminotransferase; Crt: creatinine. For each candidate predictor, left upper panel shows the overall density pooled across studies and the left lower panel shows overlapping densities normalised by relapse status. The right panel shows a univariable generalised additive model spline fit, with 95% confidence interval, of relapse.

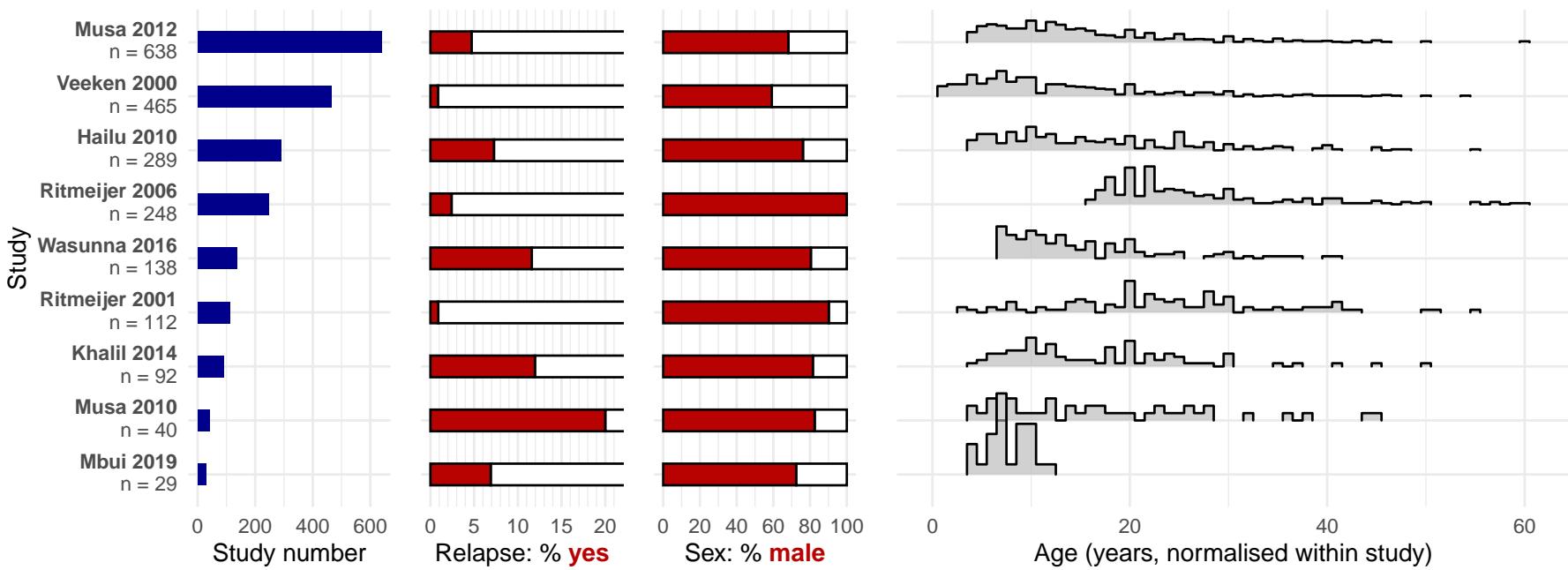


Figure 6.5: Graphical summary of East Africa study-specific sample sizes and distributions of relapse status, sex, and age.

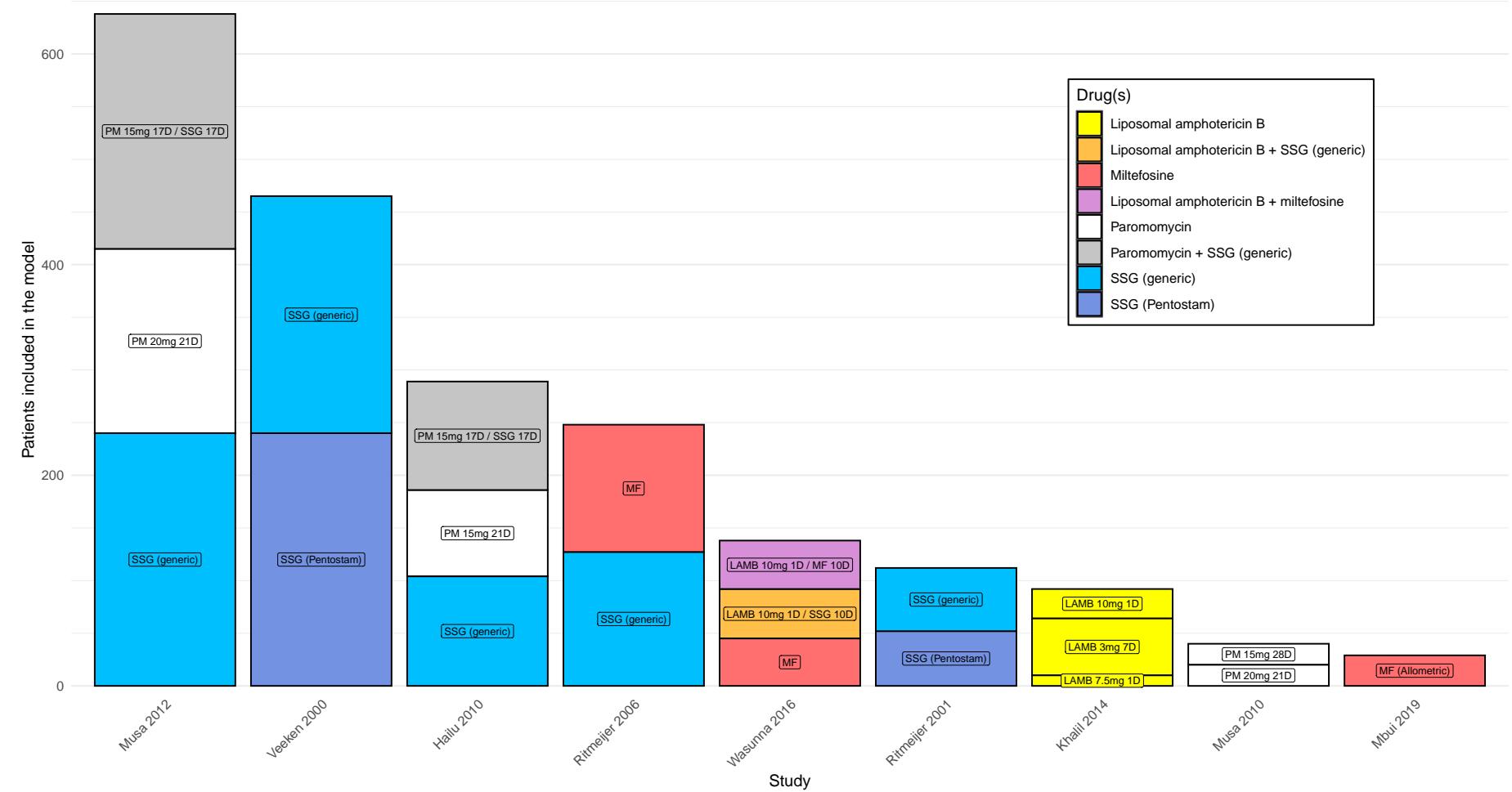


Figure 6.6: Bar chart showing the distribution of treatment regimens across contributing studies from East Africa. Drugs are colour-coded (see legend). Important distinguishing dosing information provided in the overlaying labels. Full treatment details presented in Table 6.1. D: days; LAMB: liposomal amphotericin B (Gilead); PM: paromomycin; MF: miltefosine; mg: milligrams/kilogram; SSG: sodium stibogluconate.

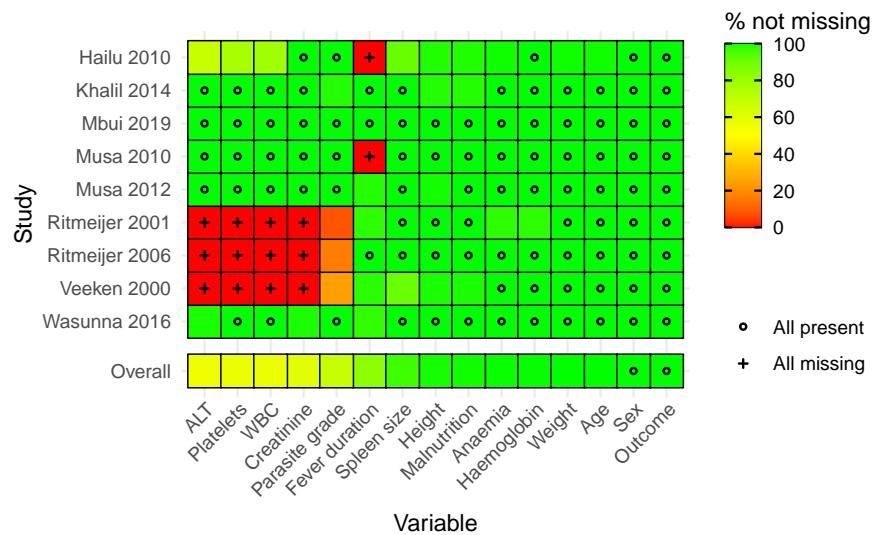


Figure 6.7: Density plot illustrating the amount of missing data overall and across contributing studies from East Africa. Study ordered by lead author and publication year. Variables ordered by amount of missingness. ALT: alanine aminotransferase; WBC: white blood cells.

6.2 Model Results

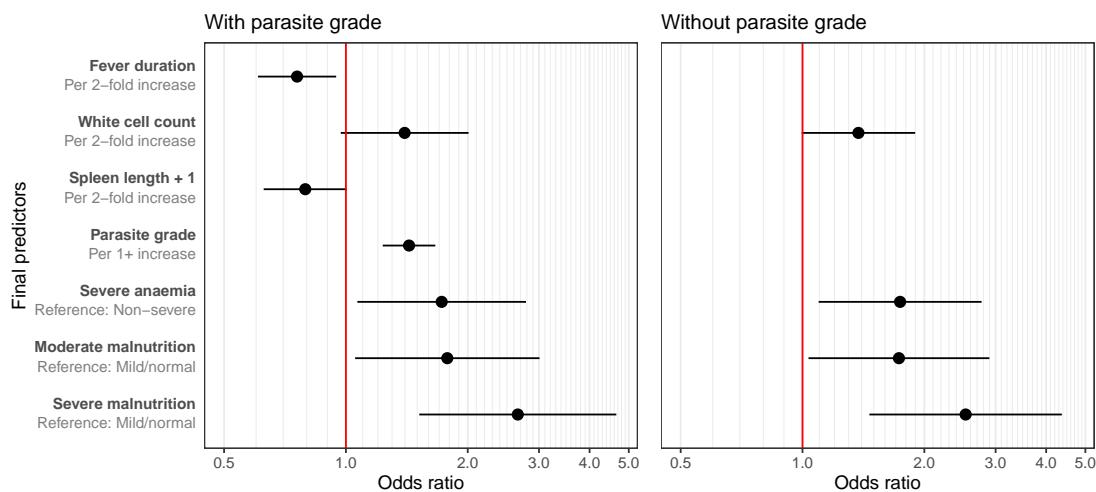
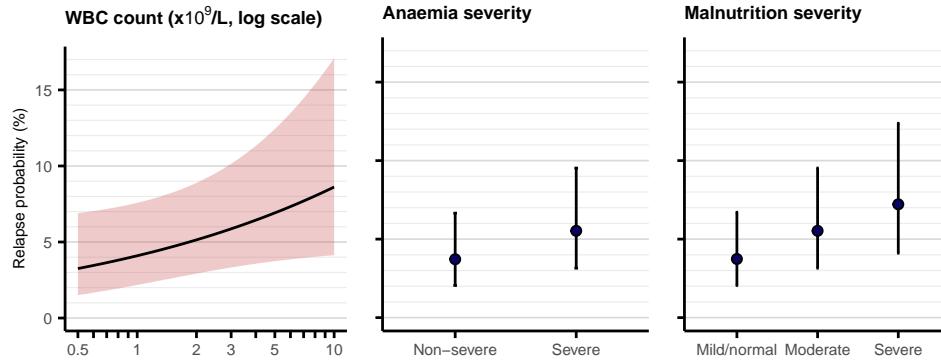


Figure 6.8: Forest plot of adjusted odds ratios with 95% confidence intervals for final model predictors. Odds ratios are displayed on a logarithmic scale.

East Africa model: without parasite grade



East Africa model: with parasite grade

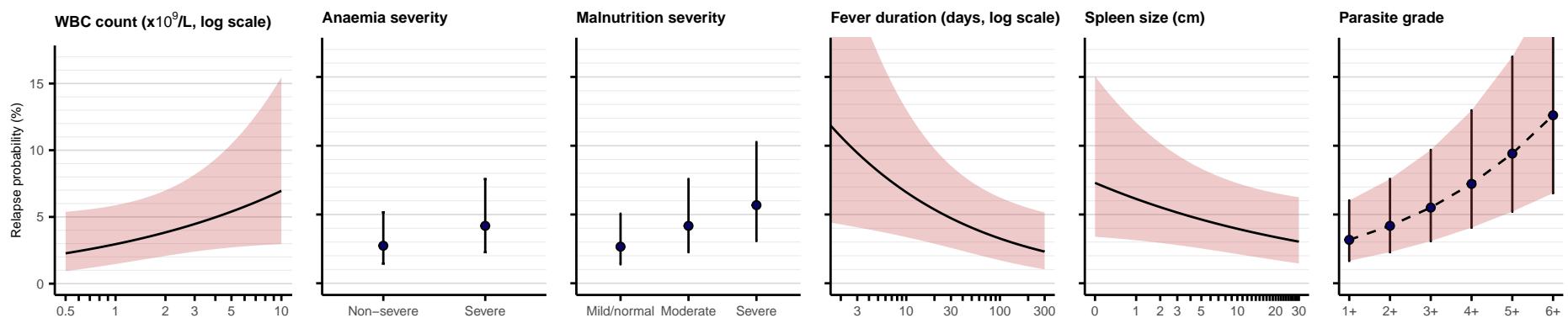


Figure 6.9: Adjusted associations between final predictors and predicted relapse probability, as estimated from the final East Africa prognostic models. Probabilities were calculated from optimism-adjusted models and following logistic recalibration (intercept-term only) to data contributed from Musa 2012[71]. Where not varying in the plot, predictions are standardised to a representative reference participant: median age (13 years), median fever duration (45 days), median white cell count ($2.5 \times 10^9/\text{L}$), with severe anaemia, moderate malnutrition, and — for the model including parasite grade — a median parasite count of 2+.

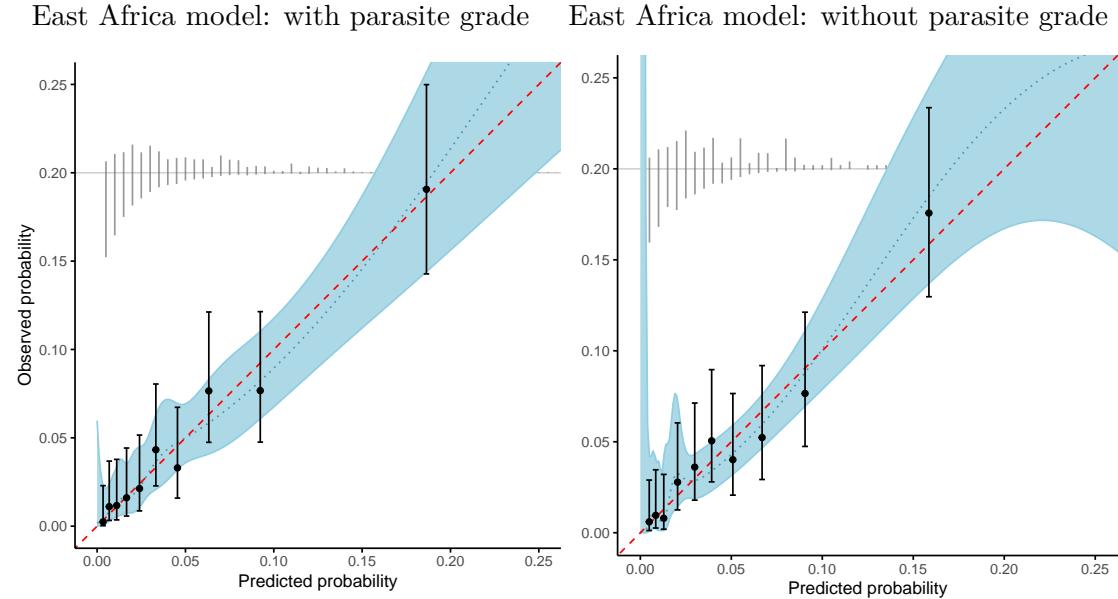


Figure 6.10: Calibration plots showing observed versus predicted probabilities for deciles of predicted probability. Red dashed line represents perfect calibration. Observed probabilities are presented with 95% confidence intervals (black error bars). A generalised additive model is fitted to show the smoothed mean observed probability (blue dotted line) with 95% confidence intervals (blue ribbon). Histograms, normalised by outcome, are overlaid to illustrate the distribution of relapses and cures across the expected probabilities.

	Performance estimate (95% CI)	Average optimism	Optimism-adjusted performance
Model: with PG			
C-statistic	0.72 (0.63–0.82)	0.046	0.68
Calibration slope	1.03 (0.64–1.42)	0.224	0.81
Model: without PG			
C-statistic	0.66 (0.56–0.76)	0.050	0.61
Calibration slope	1.08 (0.47–1.68)	0.329	0.75

Table 6.4: Apparent and optimism-adjusted performance measures. Abbreviations: CI: confidence interval; PG: parasite grade

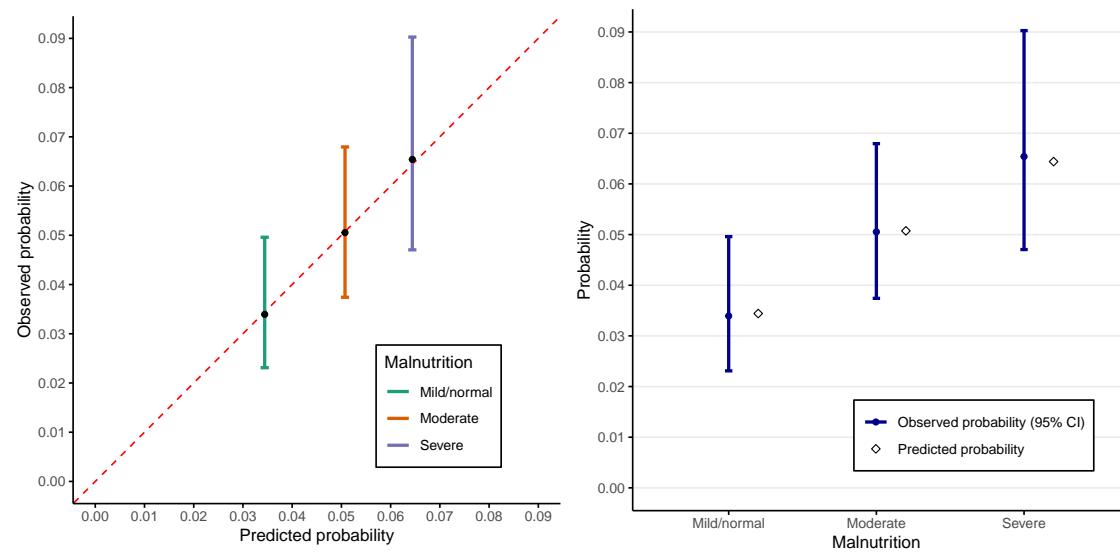


Figure 6.11: Calibration plots for malnutrition severity (model including parasite grade).

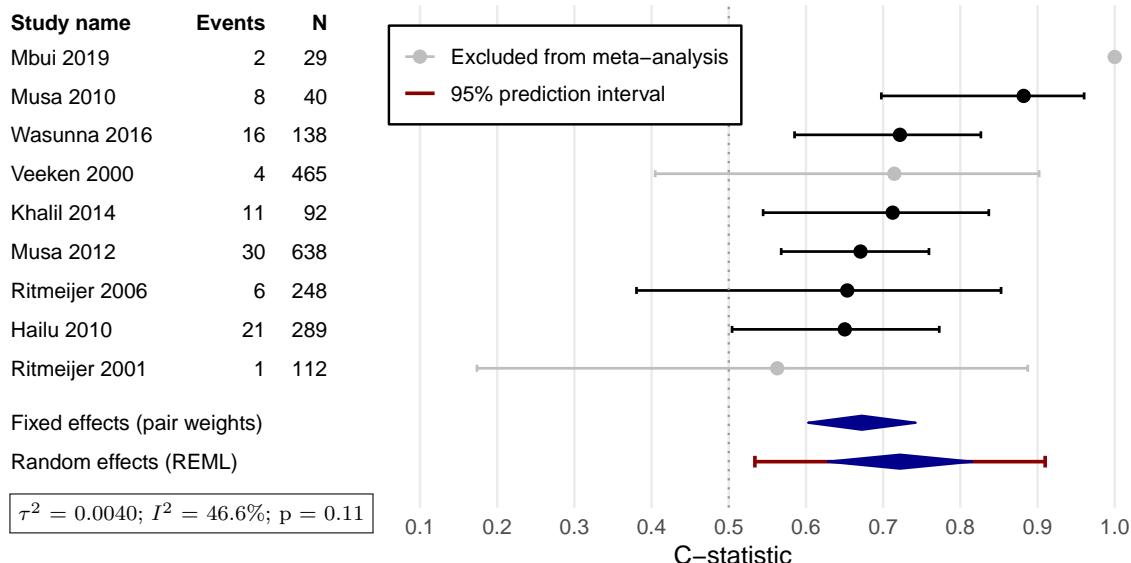


Figure 6.12: Forest plot showing individual and pooled study c-statistics, for the model including parasite grade. For the model excluding parasite grade refer to Appendix D.27. Pooled c-statistics are presented from both fixed-effects and random-effects meta-analysis models, after excluding studies with ≤ 5 relapse events. Study-specific confidence intervals with few events should be interpreted with caution (as discussed in the Methodology 4.3.7). Blue diamonds: pooled summary estimates with 95% confidence intervals. For Mbui 2019, all bootstrapped c-statistic estimates were 1 exactly and therefore no variance is presented.

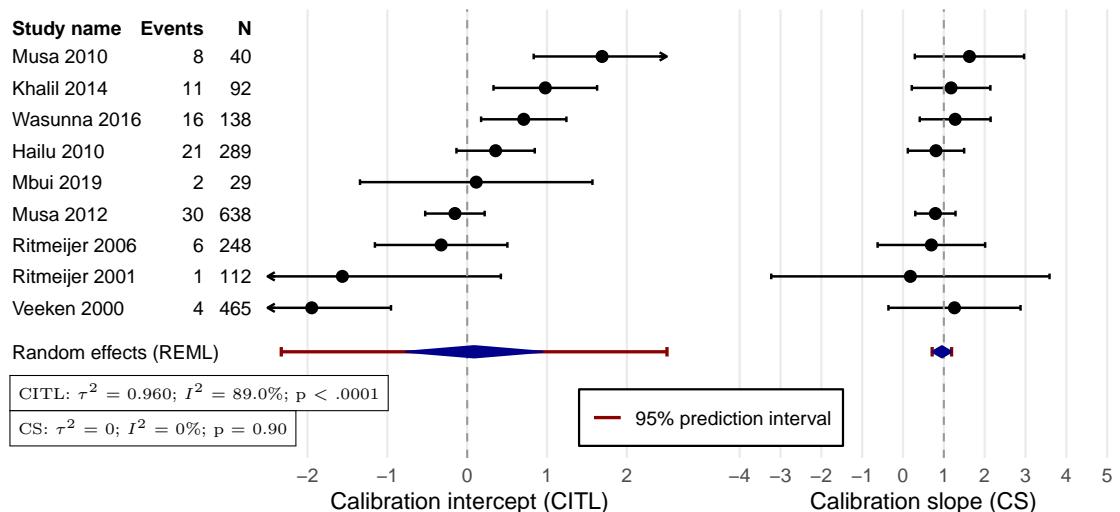


Figure 6.13: Forest plots showing individual and pooled study calibration measures for the model **including** parasite grade. Left: calibration intercept (calibration-in-the-large, CITL); Right: calibration slope (CS). Blue diamonds: summary estimates with 95% confidence intervals. Calibration slope for Mbui 2019 not shown due to small sample size causing failure of model convergence.

Quote goes here.

— James Wilson

7

Discussion

Introduction.

Principal findings.

Treatment failure risk vs. relapse risk - can we extrapolate?

Appendices

A

Appendix — Background

Contents

A.1 Background Literature Search	99
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A.1 Background Literature Search

A literature search was performed with the aim of writing a narrative review on the VL relapse. Specifically to address the following questions:

- What is the burden of relapse?
- When does relapse occur?
- What is the cause (mechanism) of relapse?
- What are the determinants of relapse?

All searches performed on August 11th 2025 on PubMed, Embase and Web of Science (Boxes A.1–A.3). Search performed from database inception. After deduplication with Covidence[242] 1,891 articles were identified. Following title and abstract review, 55 articles were identified for inclusion in the narrative review.

Inclusion criteria:

Inclusion criteria: (1) Publications looking at associations between VL relapse occurrence and host/parasite characteristics during, before, or shortly after treatment of index case. (2) Systematic/literature reviews looking at relapse determinants. (3) All ages, geographical locations.

Exclusion criteria: (1) Conference abstracts, protocols, case reports. (2) Articles not published in English. (3) Non-human studies.

Box A.1: PubMed search terms (932 hits)

```
("Leishmaniasis, Visceral"[Mesh] OR "visceral leishmaniasis" OR  
"leishmaniasis, visceral" OR "kala azar" OR "kala-azar") AND  
("Recurrence"[Mesh] OR relapse* OR recurrent OR recurrence OR  
recrudescence OR "treatment failure")
```

Box A.2: Embase search terms (1303 hits)

1. visceral leishmaniasis.mp. or exp visceral leishmaniasis/
2. kala-azar.mp.
3. 1 or 2
4. exp relapse/ or relapse*.mp.
5. recurrence*.mp. or exp recurrent disease/
6. recurrent.mp.
7. recrudescence.mp.
8. 4 or 5 or 6 or 7
9. treatment failure.mp. or exp treatment failure/
10. 8 or 9
11. 3 and 10

Box A.3: Web of Science (1097 hits)

1. TS=((Leishmaniasis and Visceral) or (Kala azar) or (Kala azar))
2. TS=((relapse\$) or (recurren\$) or (recrudescence) or (treatment failure\$))
3. #2 AND #1

B

Appendix — Model methodology

C

Appendix — Results: Indian Subcontinent Model

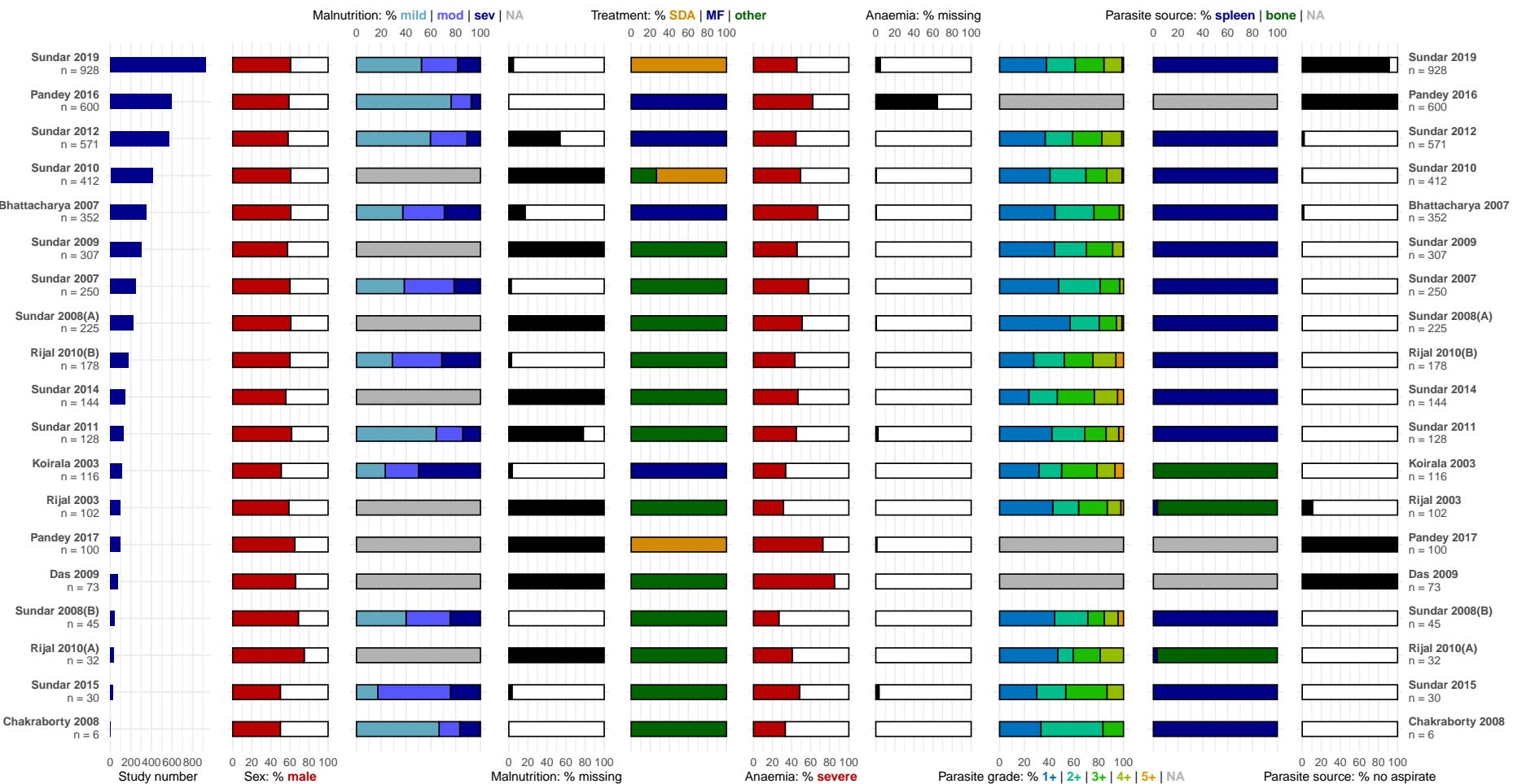


Figure C.1: Distribution of categorical predictors by study. Missing data excluded from stacked bar charts for malnutrition, parasite grade. Where aspirates were performed, the source was never missing. NA: unable to show distribution as all study-specific data are missing. MF: miltefosine; SDA: single-dose liposomal amphotericin B

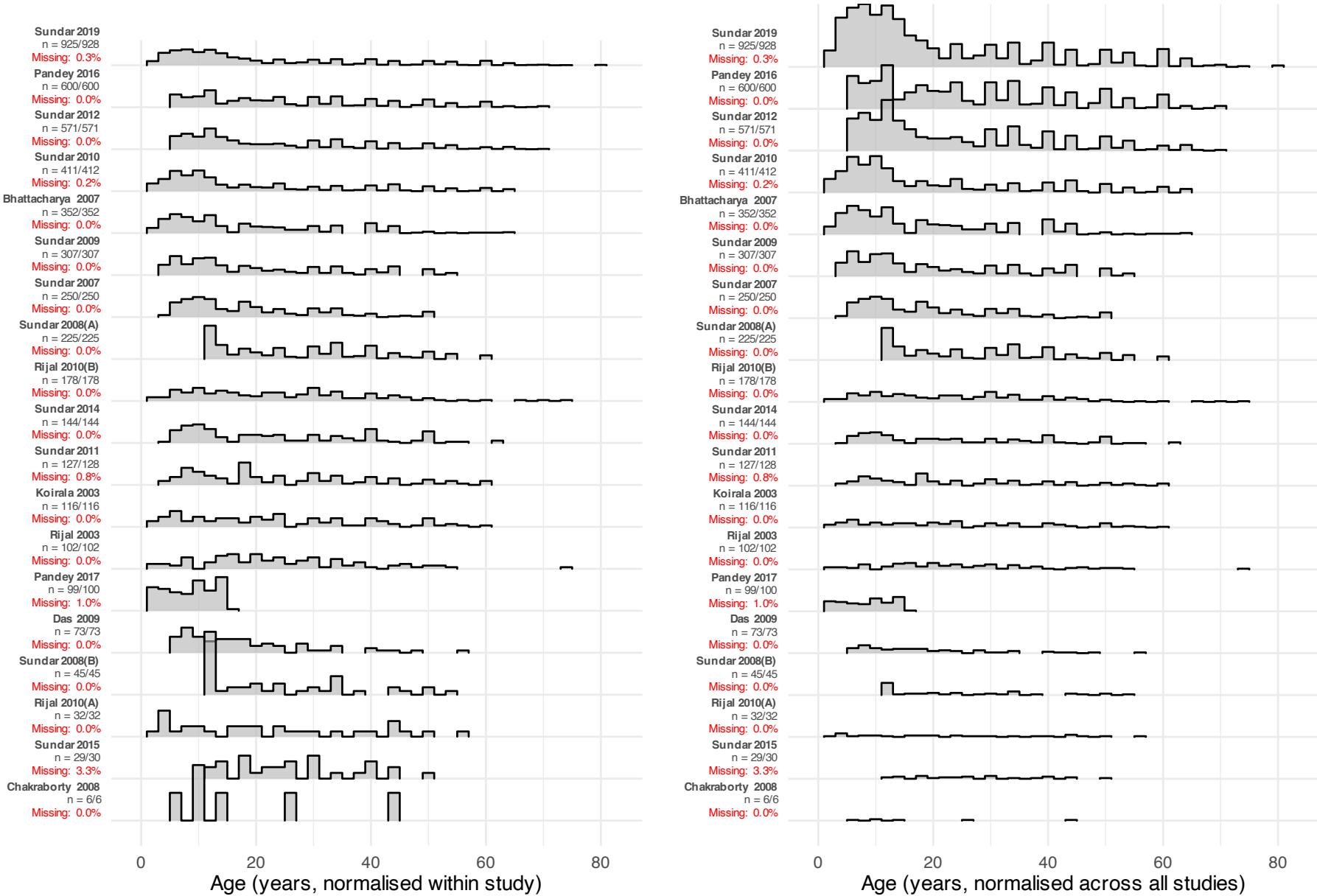


Figure C.2: Distribution of age across studies from the Indian subcontinent. Missing age data described by study.

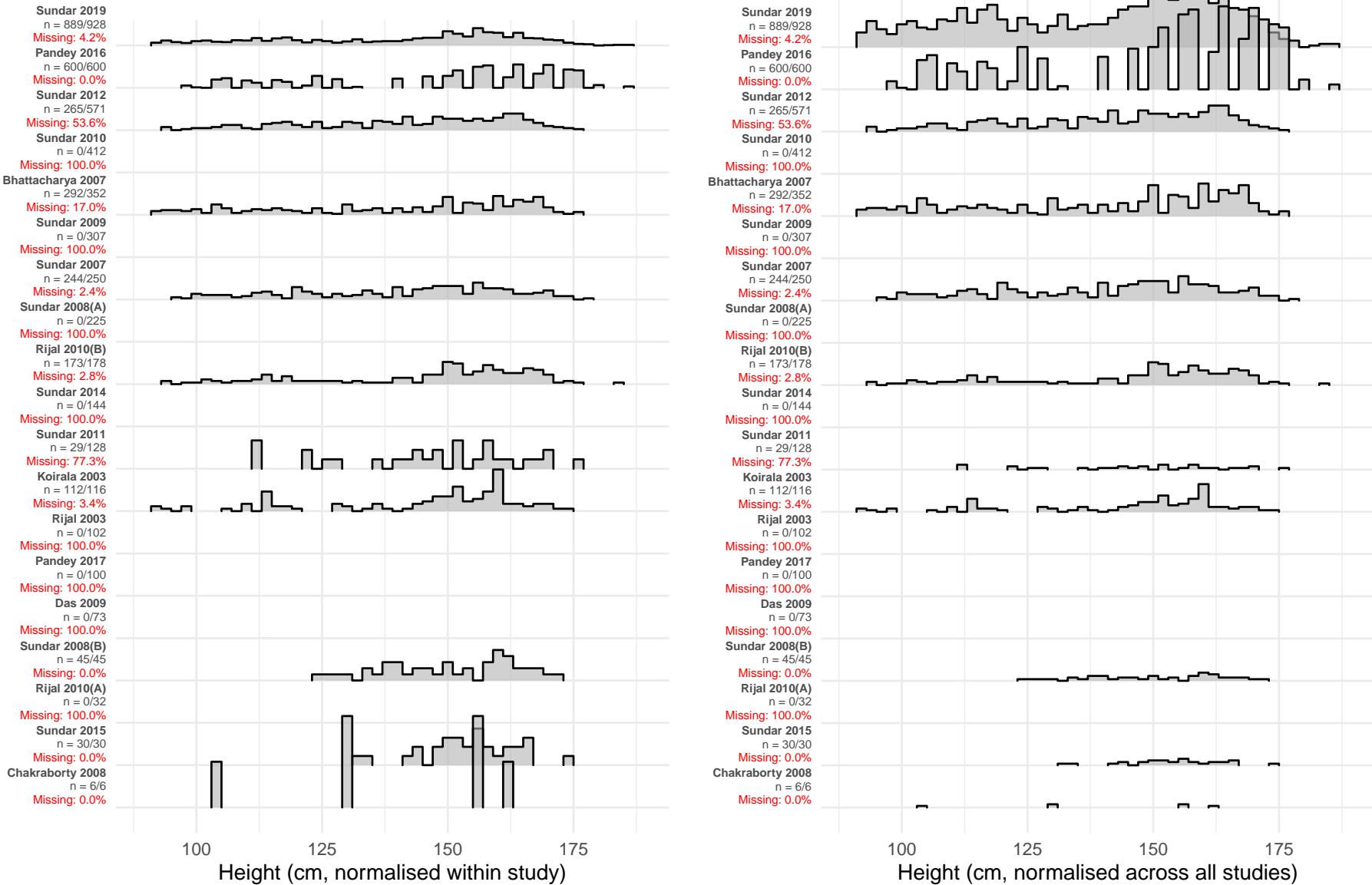


Figure C.3: Distribution of height across studies from the Indian subcontinent. Missing data described by study.

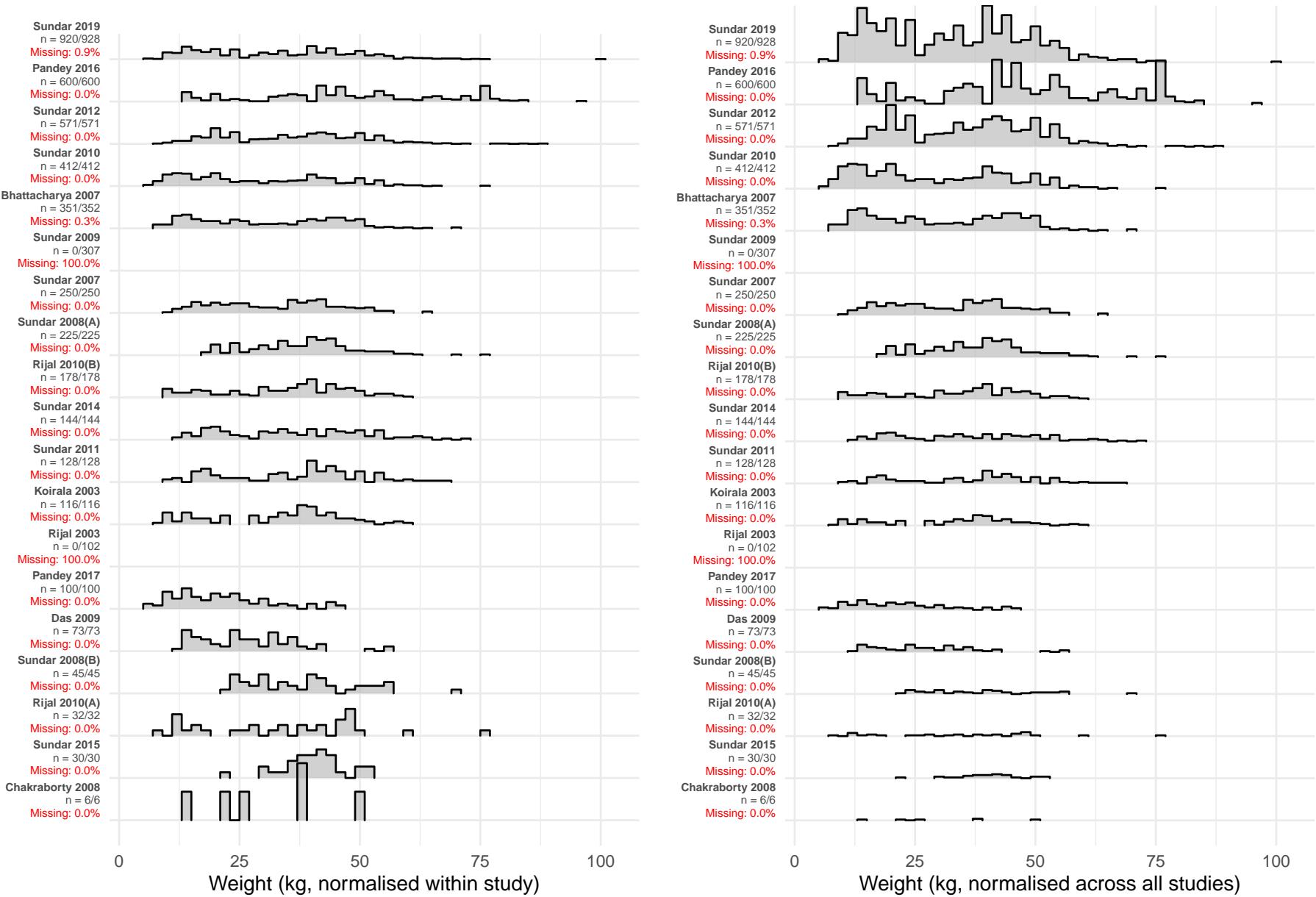


Figure C.4: Distribution of weight across studies from the Indian subcontinent. Missing data described by study.

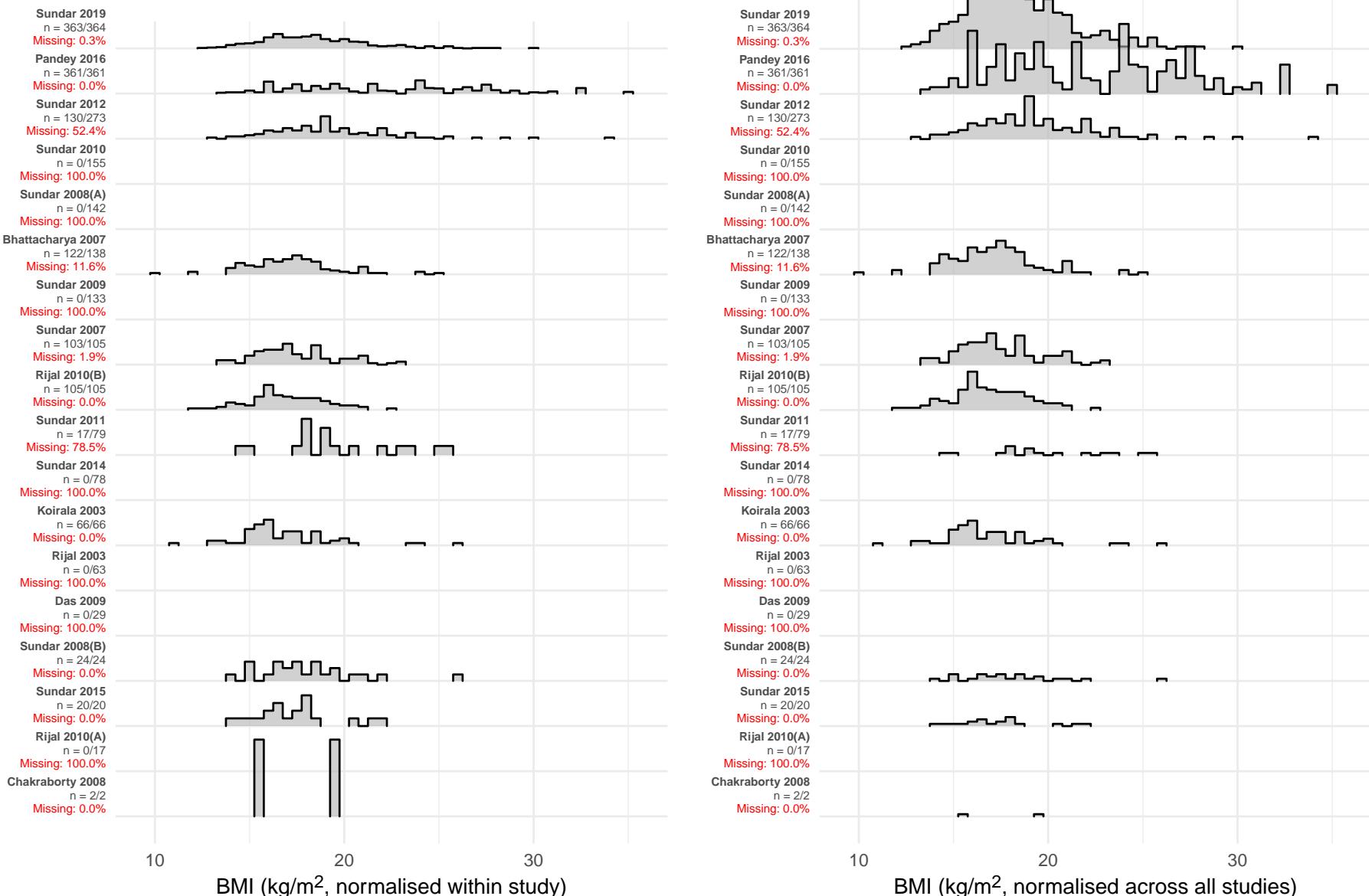


Figure C.5: Distribution of BMI across studies from the Indian subcontinent. Including only participants aged 19 and over (Pandey 2017 excluded). Missing data described by study.

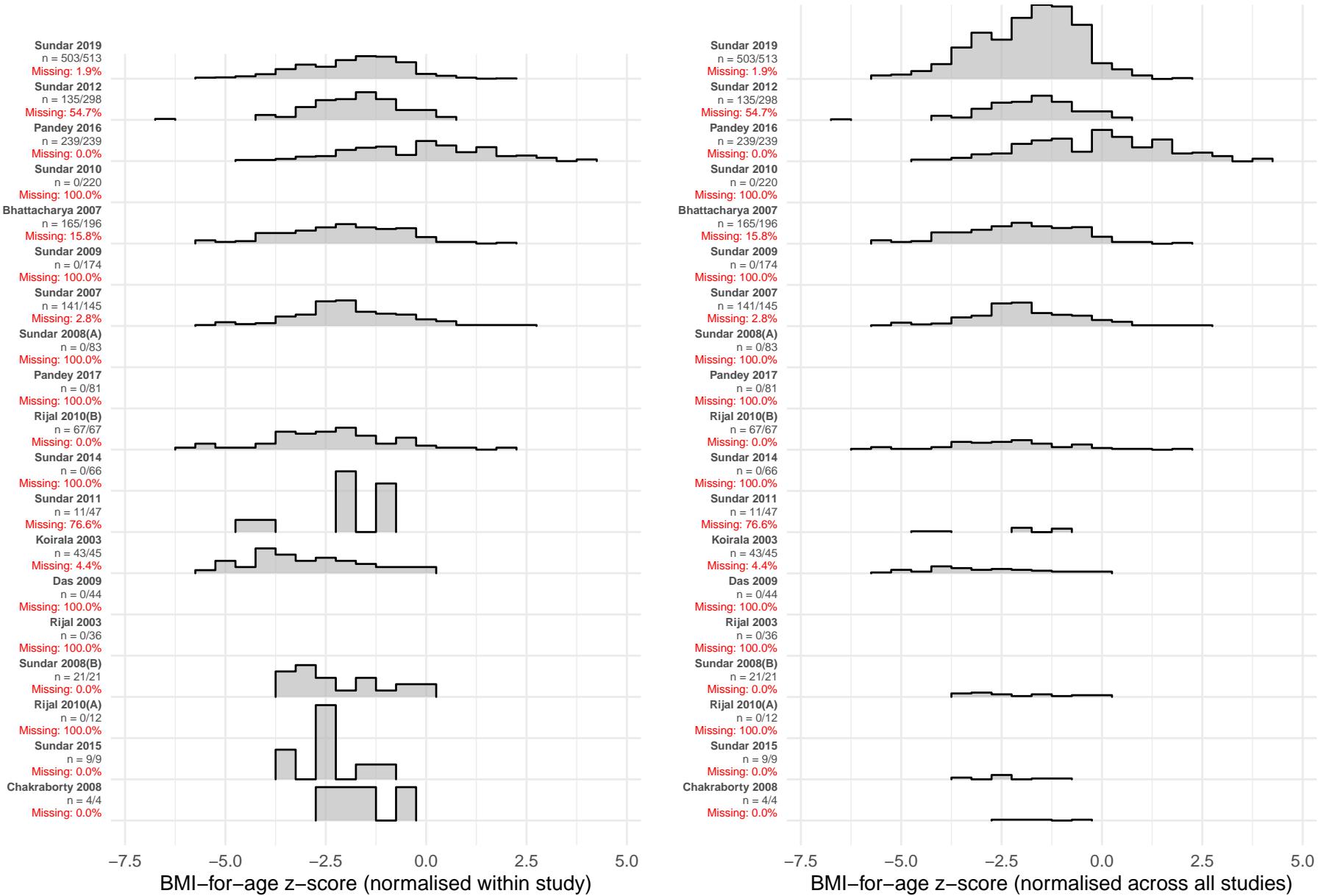


Figure C.6: Distribution of BMI-for-age z score across studies from the Indian subcontinent. Including only participants aged from 5–18, inclusive. Missing data described by study.

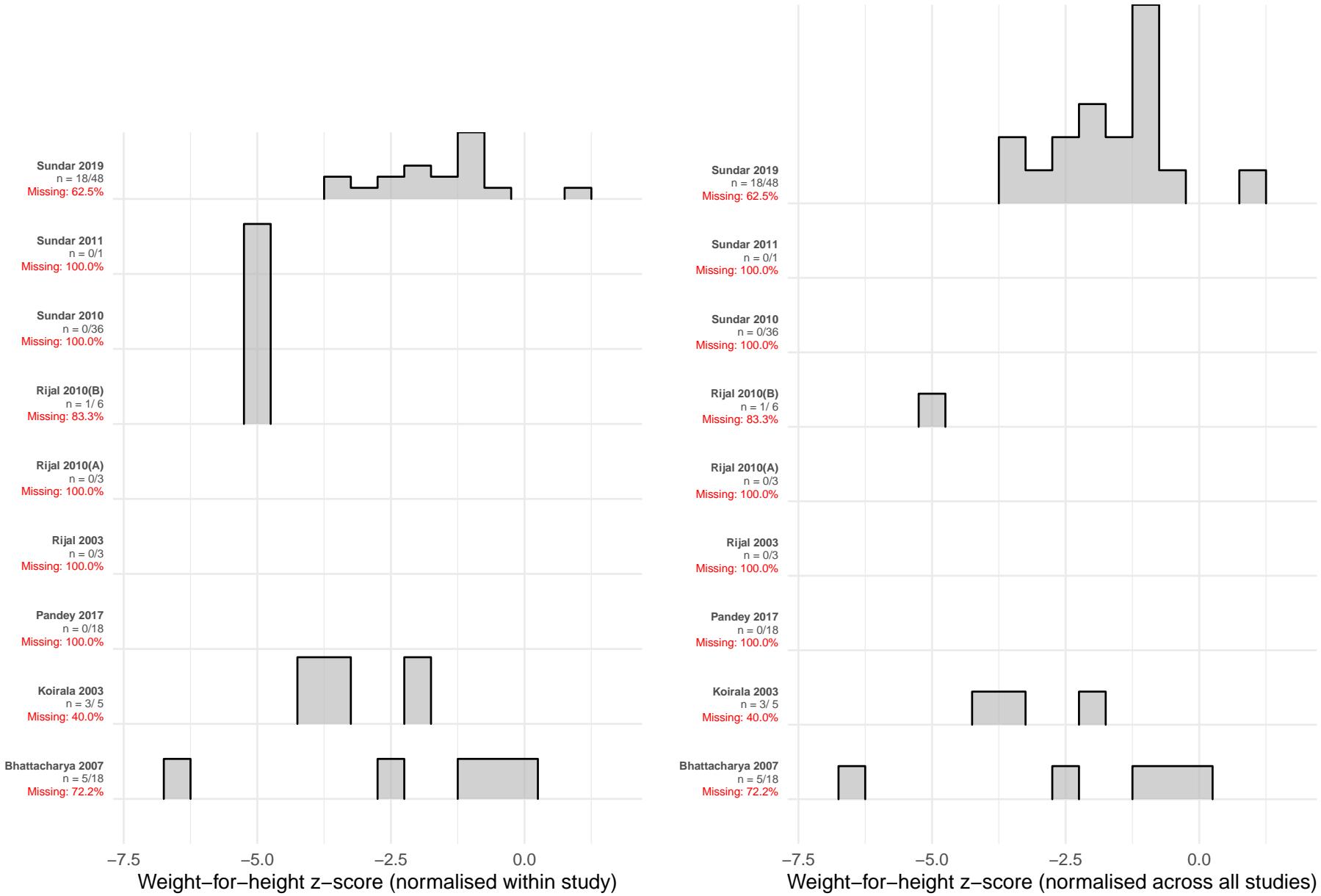


Figure C.7: Distribution of weight-for-height z score across studies from the Indian subcontinent. Including only participants aged under 5. Missing data described by study.

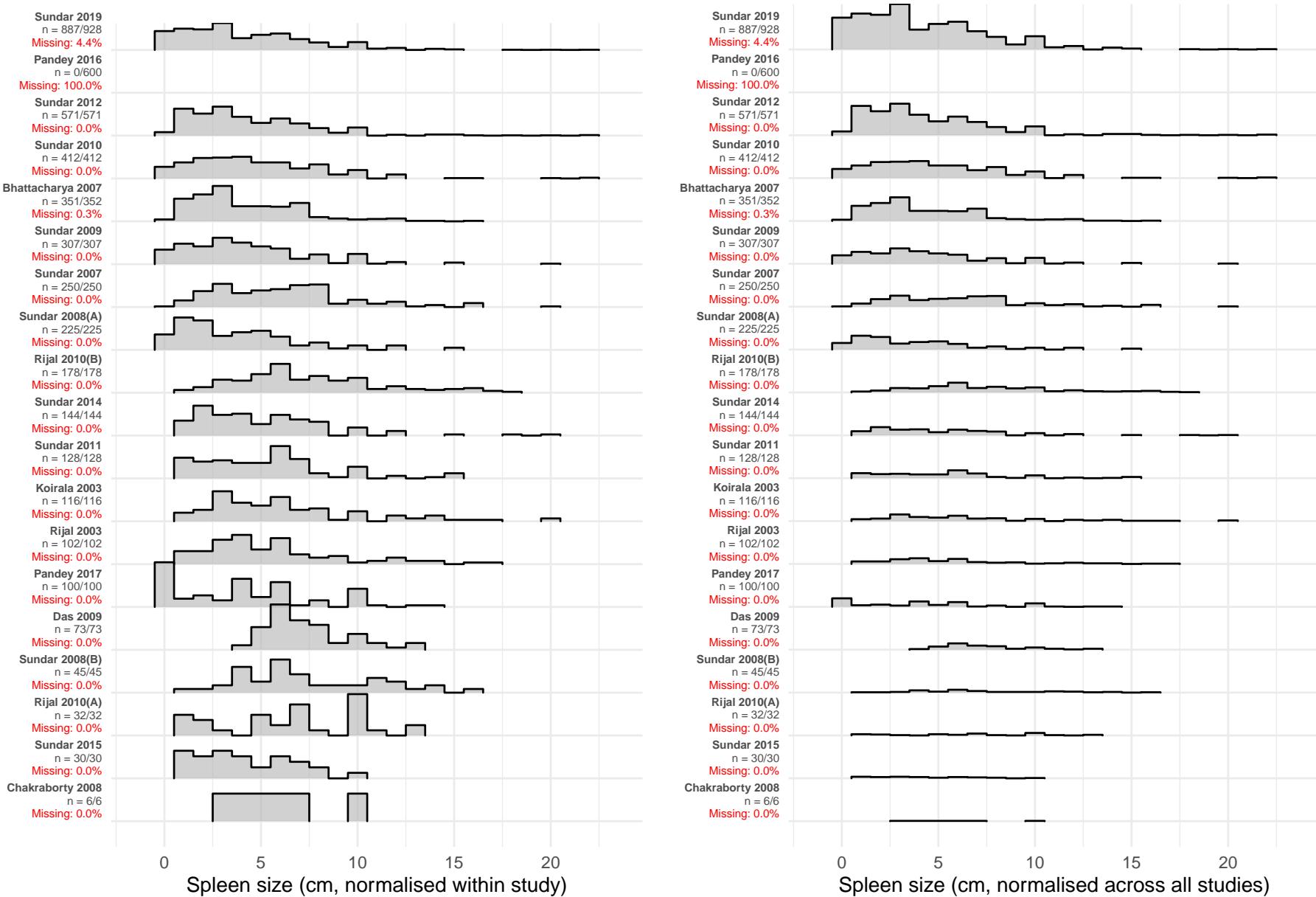


Figure C.8: Distribution of spleen size across studies from the Indian subcontinent. Missing data described by study.

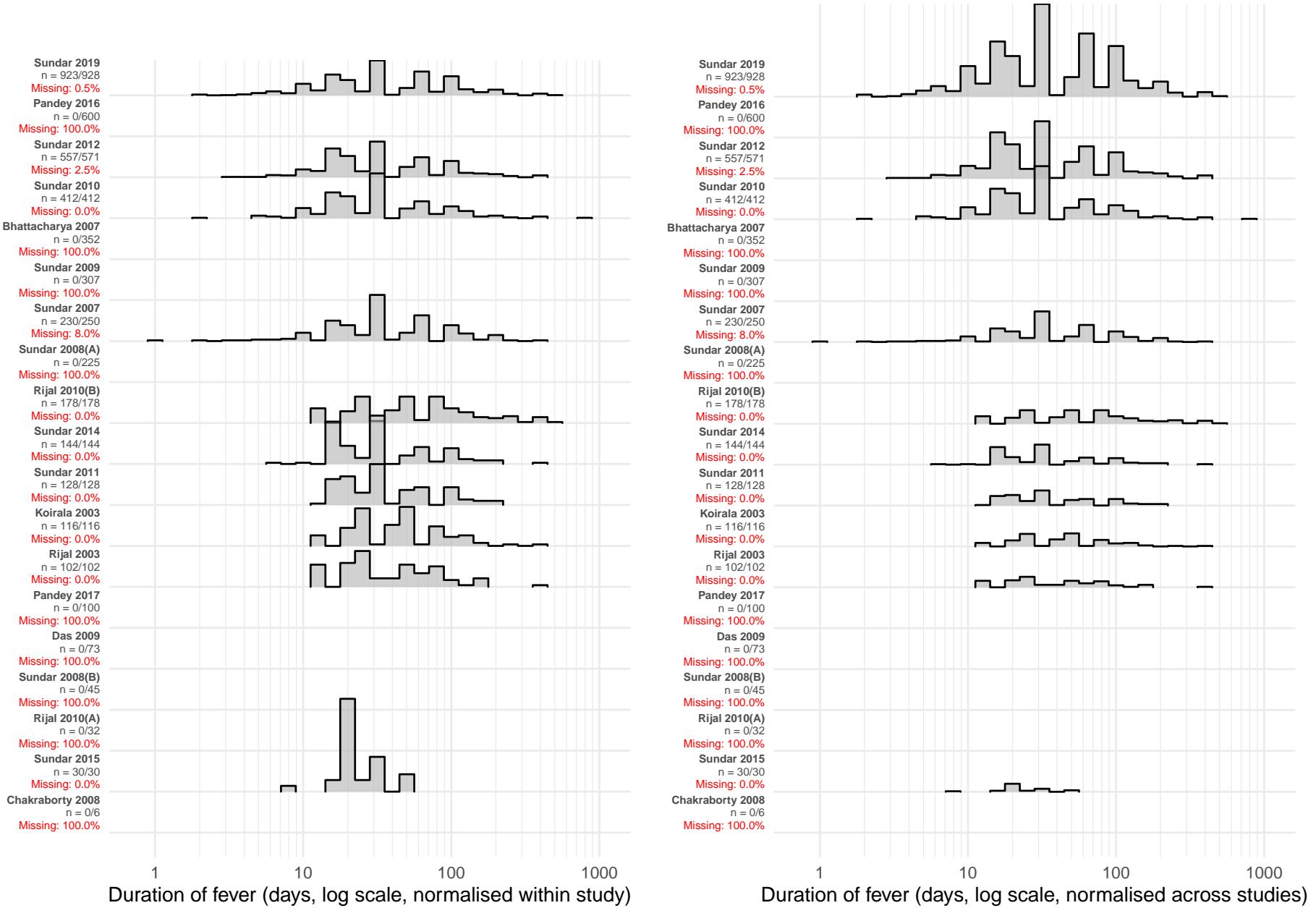


Figure C.9: Distribution of fever duration (log scale) across studies from the Indian subcontinent. Missing data described by study.

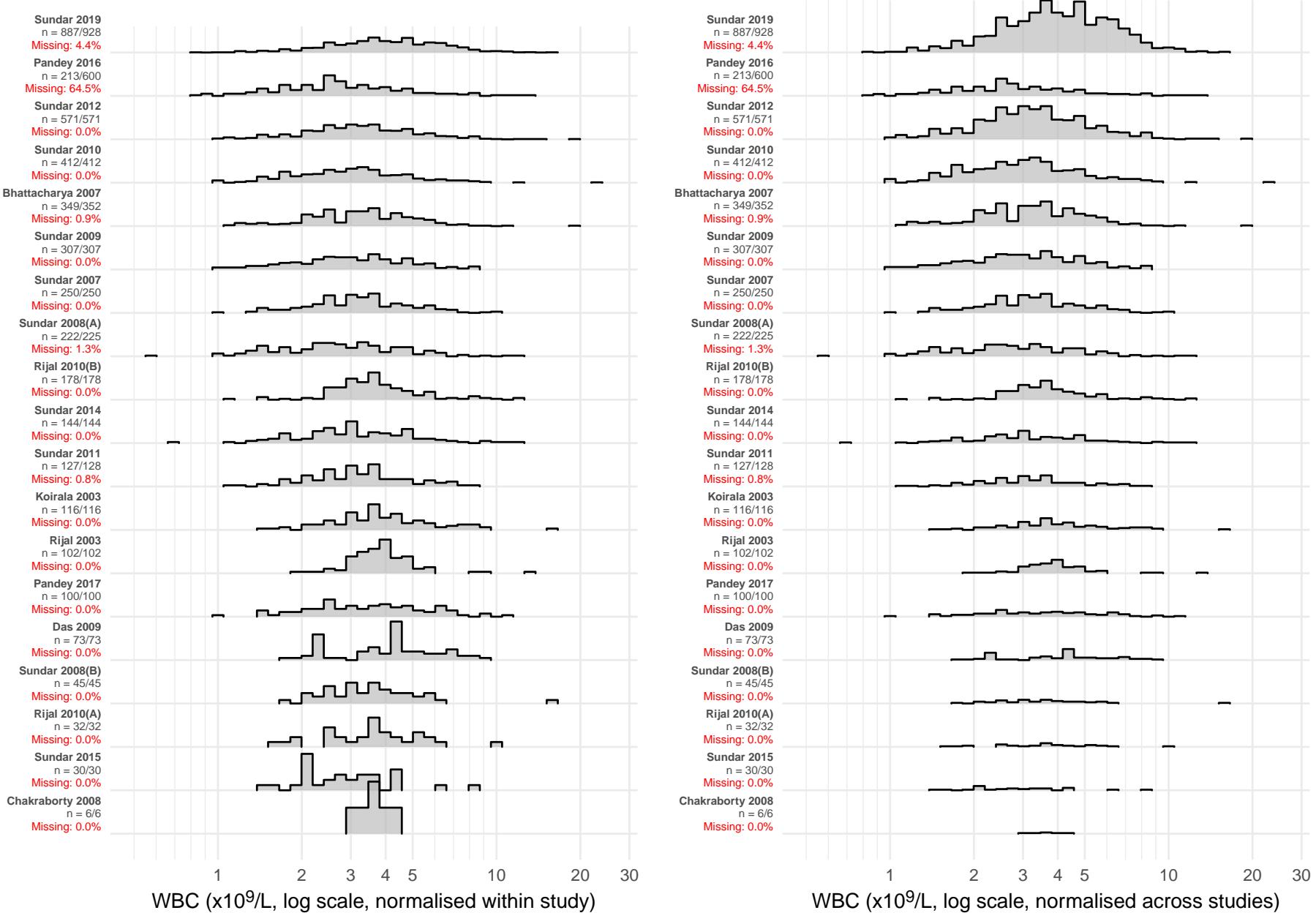


Figure C.10: Distribution of white blood cell count (log scale) across studies from the Indian subcontinent. Missing data described by study.

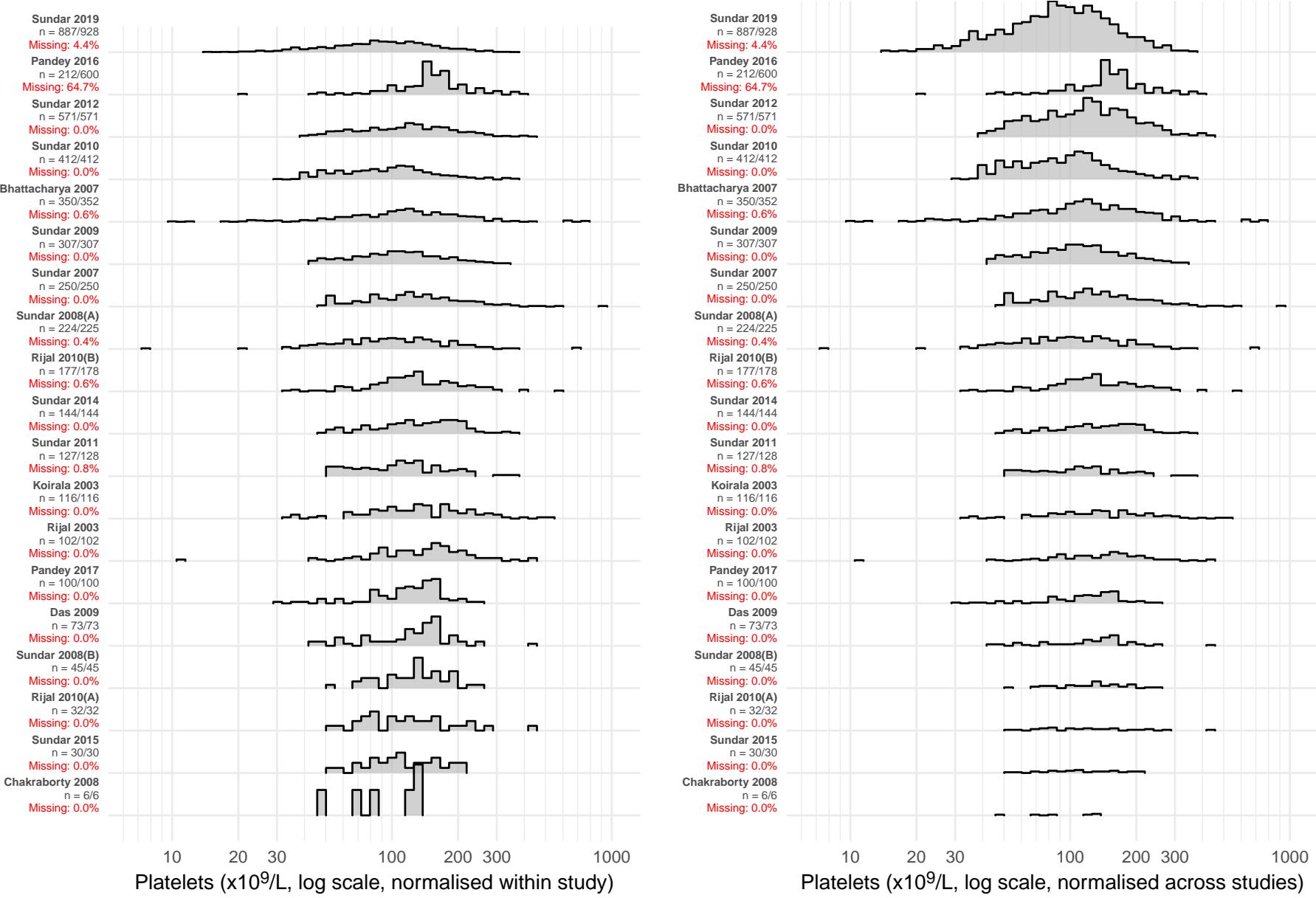


Figure C.11: Distribution of platelet count (log scale) across studies from the Indian subcontinent. Missing data described by study.

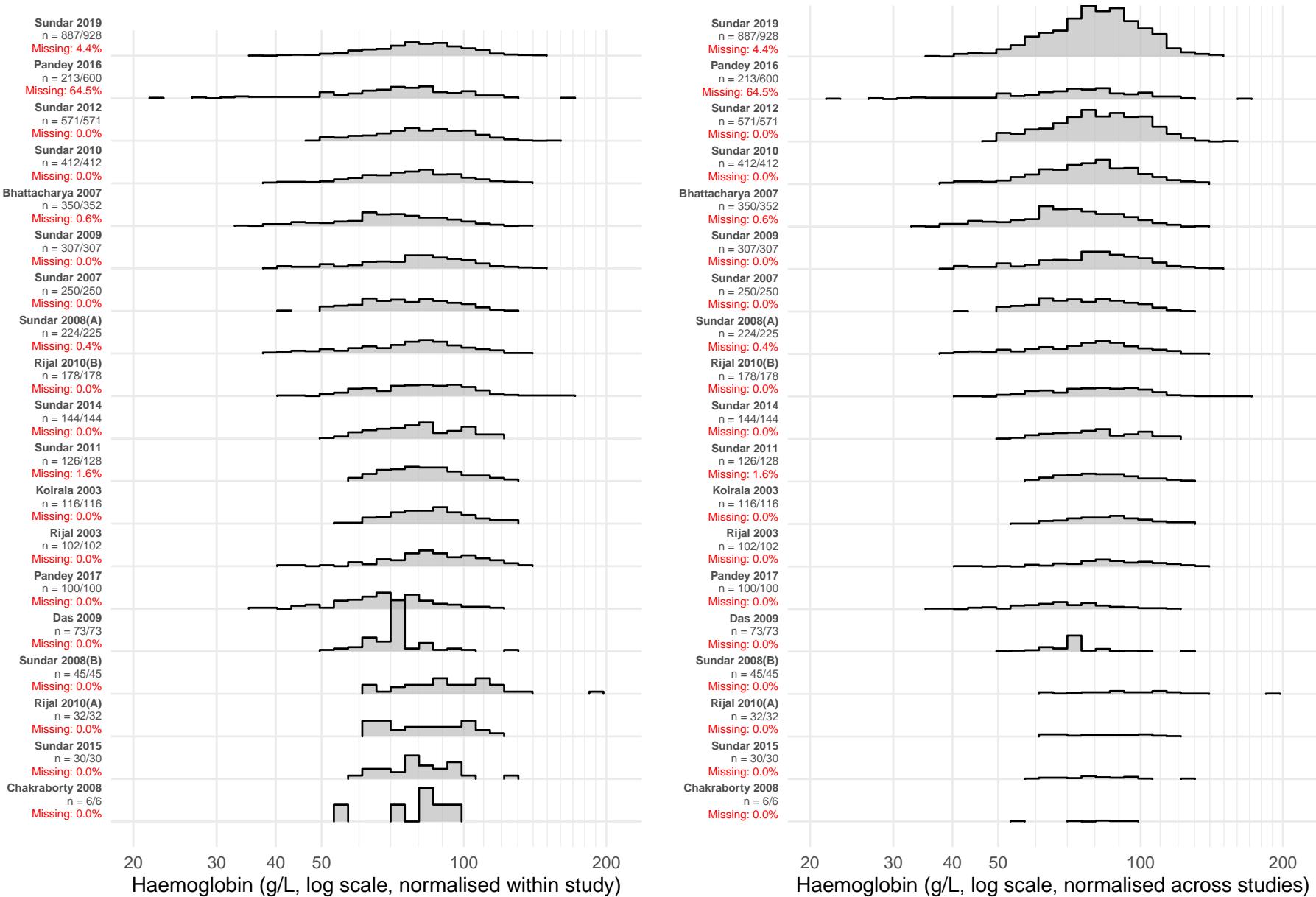


Figure C.12: Distribution of haemoglobin (log scale) across studies from the Indian subcontinent. Missing data described by study.

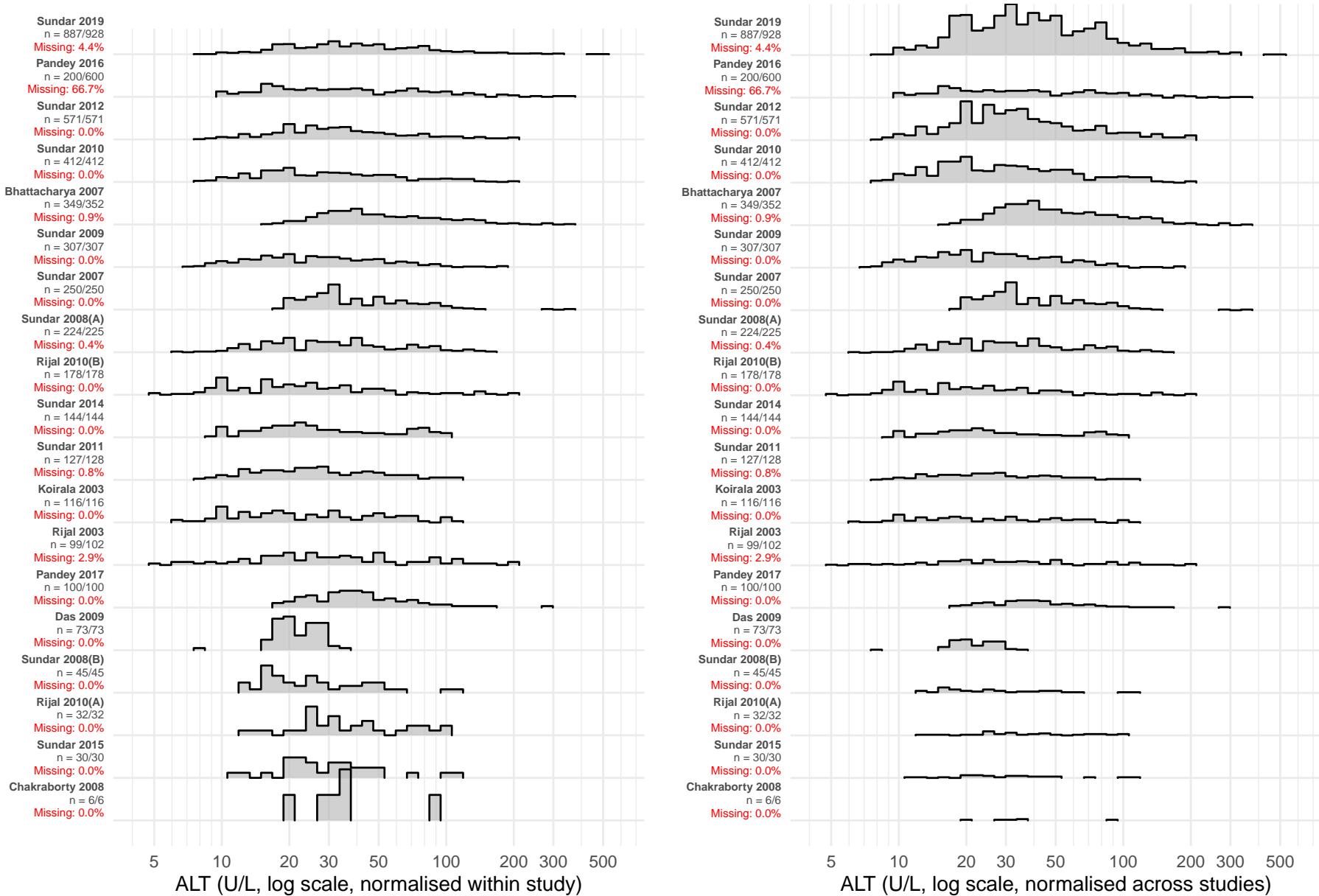


Figure C.13: Distribution of alanine transaminase (ALT, log scale) across studies from the Indian subcontinent. Missing data described by study.

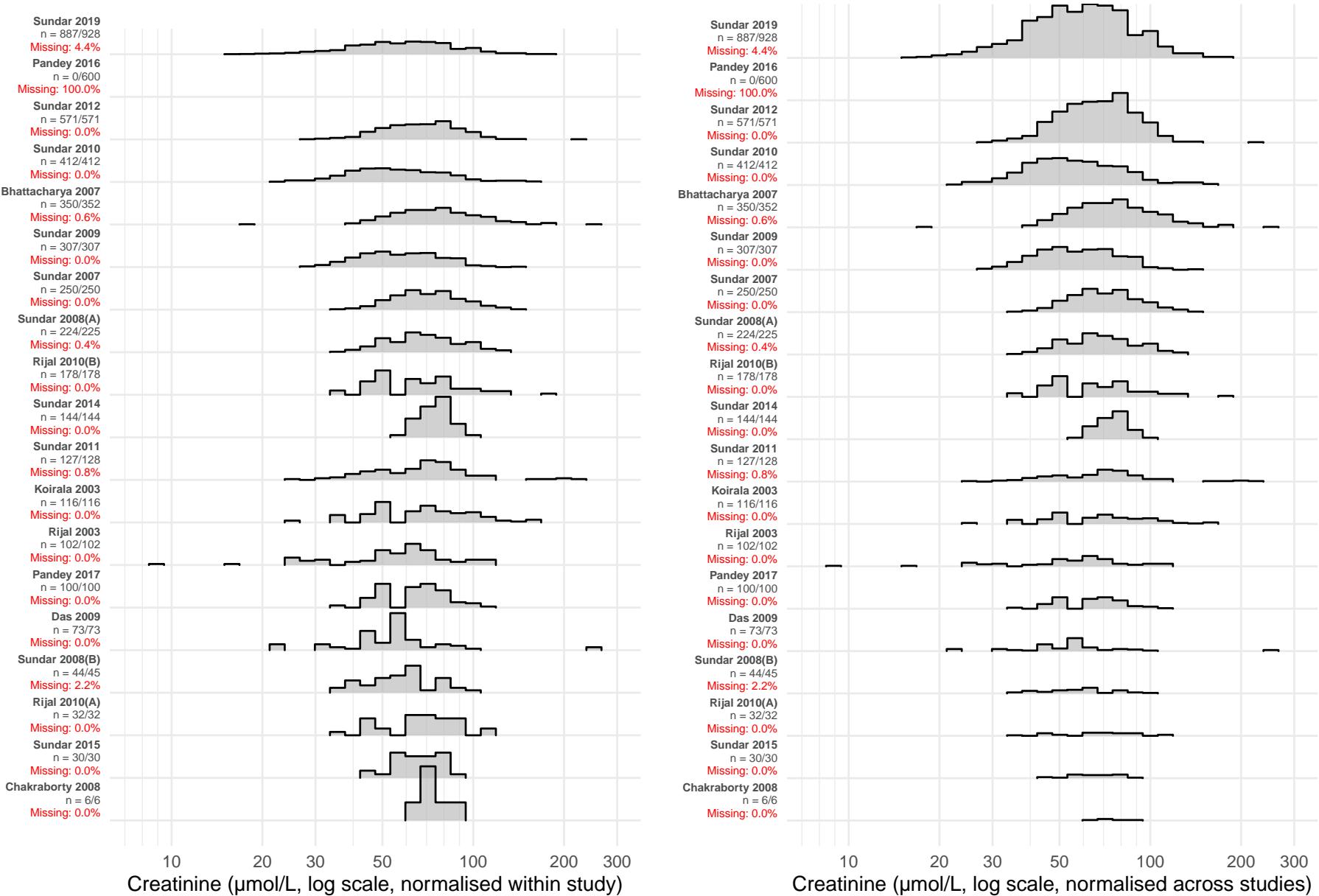


Figure C.14: Distribution of creatinine (log scale) across studies from the Indian subcontinent. Missing data described by study.

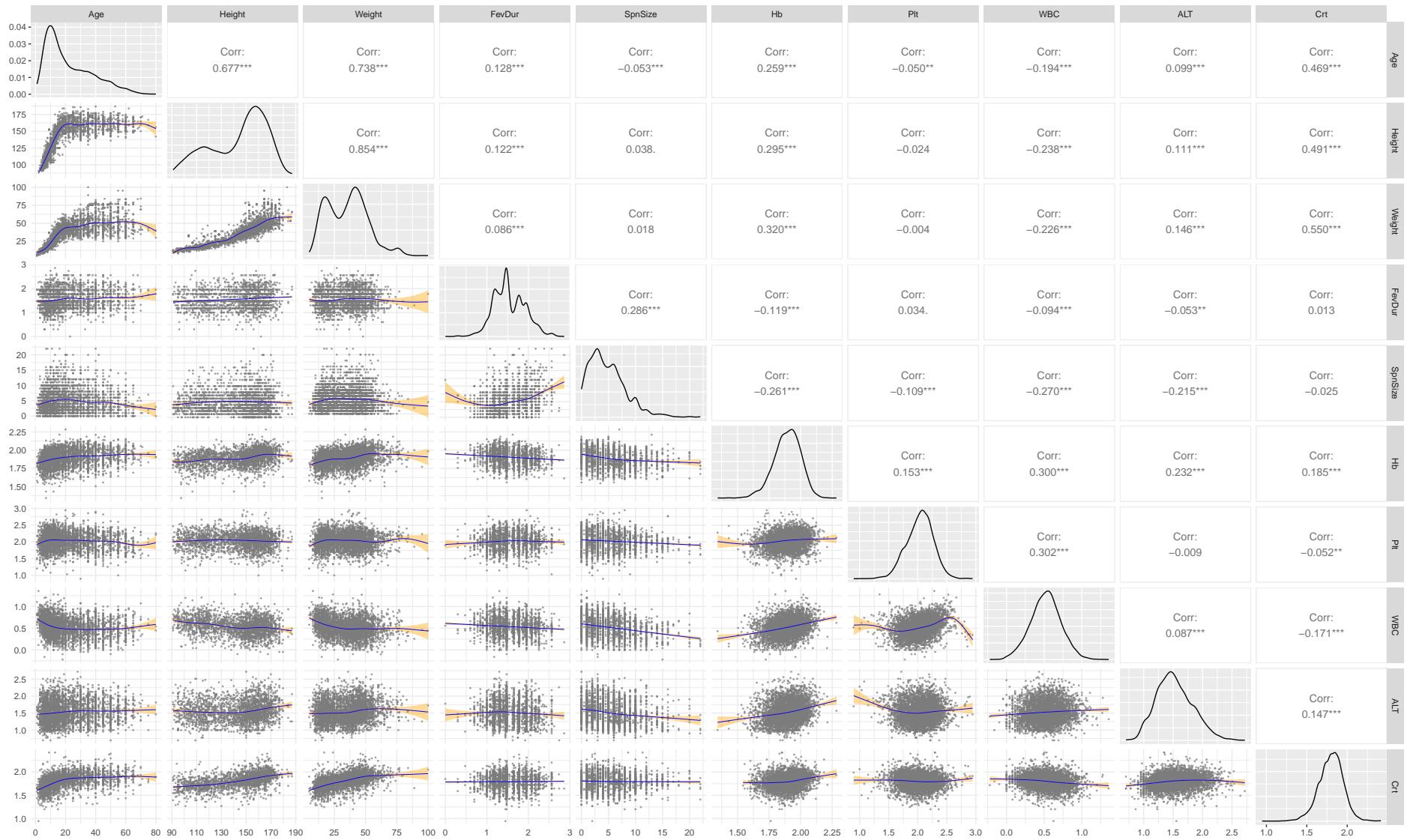


Figure C.15: Correlation between continuous variables. For scatter plots, a univariable generalised additive model is fitted (blue line) with 95% confidence interval ribbon filled (orange area). Pearson correlation coefficients are presented, ‘***’ $p<0.001$; ‘**’ $p<0.01$; ‘*’ $p<0.05$; ‘.’ $p<0.10$. Age: years; Height: cm; Weight: kg; FevDur: duration of fever, log10(days); SpnSize: spleen size (cm); Hb: haemoglobin, log10(g/L); Plt: platelets, log10($\times 10^9/L$); WBC: white blood cells log10($\times 10^9/L$); ALT: alanine aminotransferase, log10(U/L); Cr: creatinine log10($\mu\text{mol}/L$).

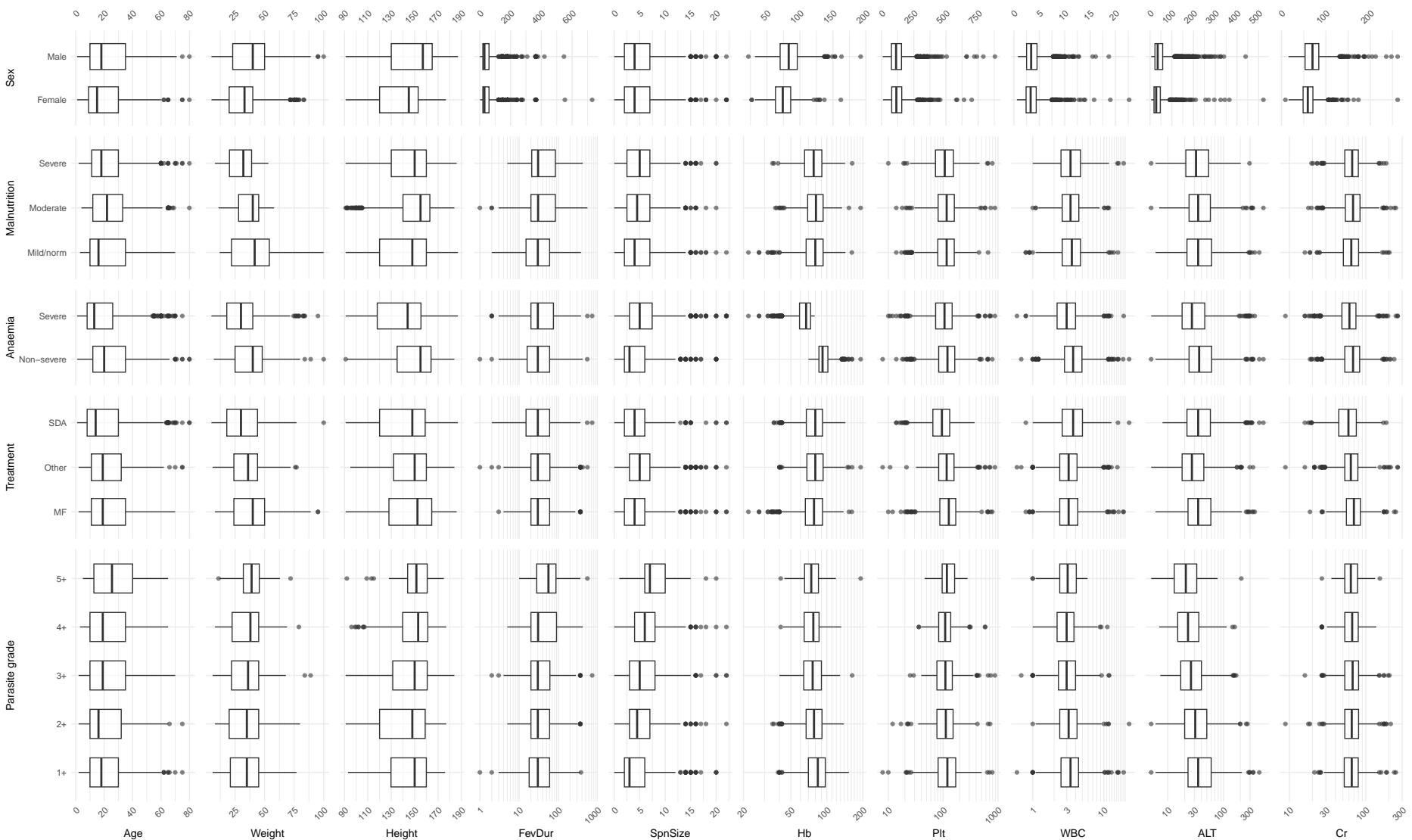


Figure C.16: Correlation between continuous and categorical variables. FevDur and laboratory tests axes transformed to log10 scale. Age: years; Height: cm; Weight: kg; FevDur: duration of fever, days; SpnSize: spleen size, cm; Hb: haemoglobin, g/L; Plt: platelets, $\times 10^9/L$; WBC: white blood cells $\times 10^9/L$; ALT: alanine aminotransferase, U/L; Cr: creatinine $\mu\text{mol}/L$.

term	estimate ¹	std.error	t statistic	df (effective)	p value
Fixed intercept	-2.9166	0.2592	-11.25	1123.60	6.54E-28
Parasite grade ²	0.2669	0.0781	3.42	174.73	7.88E-04
Age (linear) ³	-0.2352	0.0975	-2.41	3222.98	1.59E-02
Age (squared) ³	0.1352	0.0658	2.05	4178.35	4.00E-02
Anaemia: Severe ⁴	-0.3860	0.1597	-2.42	875.81	1.59E-02
Fever duration ⁵	-0.5594	0.1175	-4.76	77.95	8.68E-06
Treatment: SDA ⁶	-0.8349	0.3483	-2.40	3059.66	1.66E-02
Treatment: Other ⁶	-0.7159	0.2880	-2.49	2905.85	1.30E-02
Unadjusted intercept (Sundar 2019):	-2.9888				
Uniform shrinkage factor:	0.9132				
Adjusted intercepts after shrinkage: Average:	-3.1608; Sundar 2019:	-3.2514			
Pooled τ^2 :	0.1209.	Pooled ICC:	0.0354		

¹ Logit scale before uniform shrinkage.

² Continuous variable, from 1+ to 6+ as described by Chulay and Bryceson[51]. Transformed $x \mapsto x - 1$.

³ Units: years. Standardised by mean (22.301633) and standard deviation (15.4159649).

⁴ Reference group: non-severe anaemia.

⁵ Units: days. Converted to natural log scale and then standardised by mean (3.550509) and standard deviation (0.8693318).

⁶ Reference group: standard dose miltefosine.

Table C.1: Model coefficients pooled across 30 imputed datasets using Rubin's Rules. Model **including** parasite grade. df: degrees of freedom; SDA: single dose liposomal amphotericin B; std.error: standard error

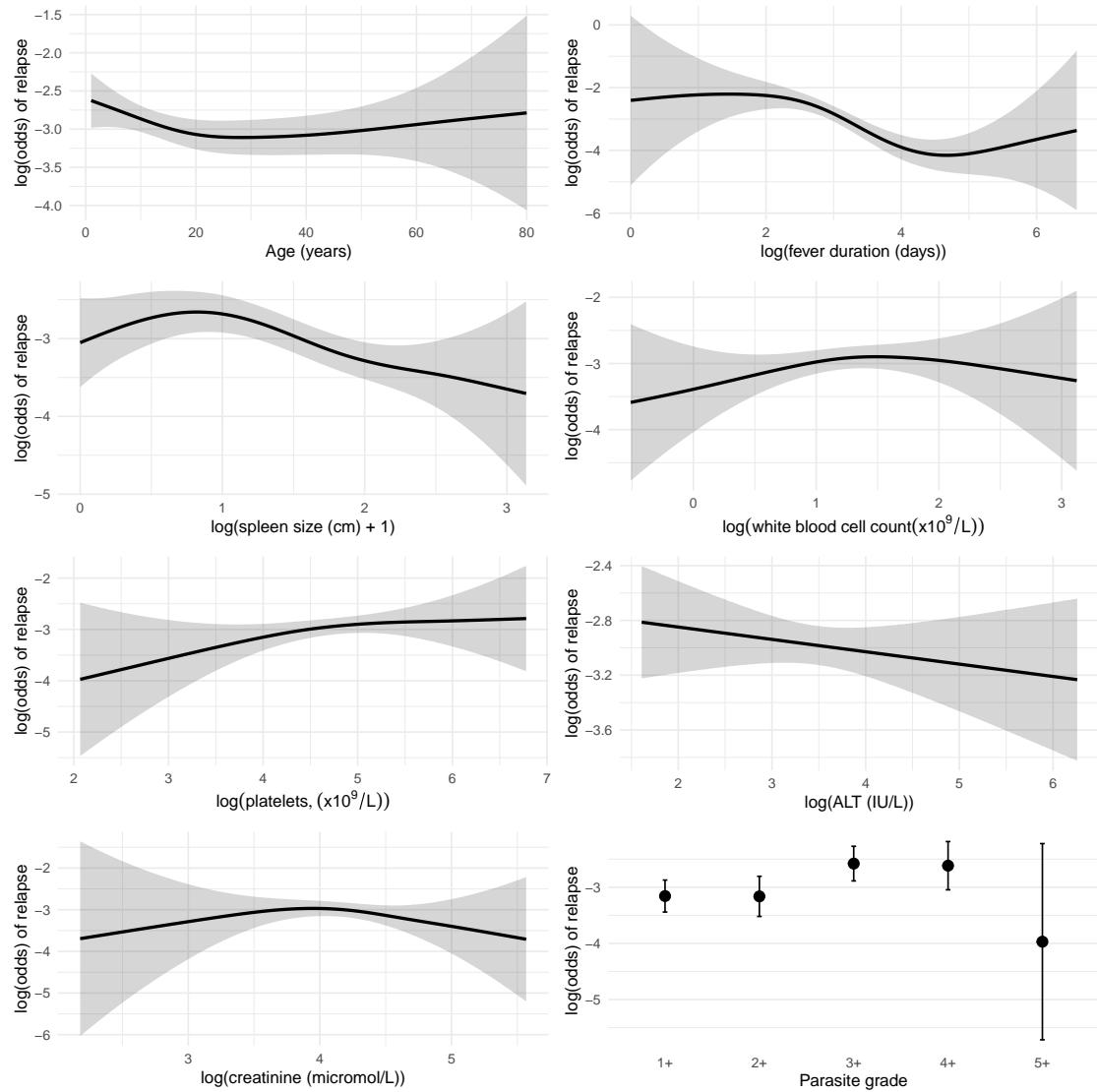


Figure C.17: Associations between transformed continuous predictors and $\log(\text{odds})$ of relapse. For each predictor (excluding parasite grade), a univariable generalised additive model spline fit is shown, with 95% confidence intervals. For parasite grade, 95% confidence intervals are calculated for each grade using the Wilson method.

term	estimate ¹	std.error	t statistic	df	p.value
Fixed intercept	-2.6042	0.2547	-10.22	2137.17	5.51E-24
Age (linear) ²	-0.2161	0.0962	-2.25	3968.52	2.47E-02
Age (squared) ²	0.1434	0.0645	2.22	4413.49	2.62E-02
Anaemia: Severe ³	-0.2921	0.1501	-1.95	2350.48	5.17E-02
Fever duration ³	-0.5221	0.1057	-4.94	107.97	2.86E-06
Treatment: SDA ⁴	-0.8438	0.3696	-2.28	3813.56	2.25E-02
Treatment: Other ⁴	-0.7571	0.3078	-2.46	2506.34	1.40E-02
Unadjusted intercept (Sundar 2019):	-2.7030				
Uniform shrinkage factor:	0.9174				
Adjusted intercepts after shrinkage: Average:	-2.8425; Sundar 2019:	-2.9543			
Pooled τ^2 :	0.1507.	Pooled ICC:	0.0437		

¹ Logit scale before uniform shrinkage.

² Units: years. Standardised by mean (22.301633) and standard deviation (15.4159649).

³ Reference group: non-severe anaemia.

⁴ Units: days. Converted to natural log scale and then standardised by mean (3.550509) and standard deviation (0.8693318).

⁵ Reference group: standard dose miltefosine.

Table C.2: Model coefficients pooled across 30 imputed datasets using Rubin's Rules. Model **excluding** parasite grade. df: degrees of freedom; SDA: single dose liposomal amphotericin B; std.error: standard error

Predictors	Model with PG	Model without PG
Fever duration	500¹	500¹
Parasite grade	472¹	n/a
Age (linear)	418¹	415¹
Age (squared)	355¹	392¹
Treatment	333¹	337¹
Anaemia	314¹	263¹
Spleen size	244	120
Sex	209	217
Age (cubic)	114	150
ALT	86	184
Platelets	78	78
WBC	51	55
Malnutrition	33	26
Creatinine	30	30

¹ Selected in final model.

Table C.3: Frequency of predictor selection during 500 bootstrap model developments. Predictors sorted by selection frequency in the model with parasite grade. ALT: alanine aminotransferase; n/a: not applicable; PG: parasite grade; WBC: white blood cell count

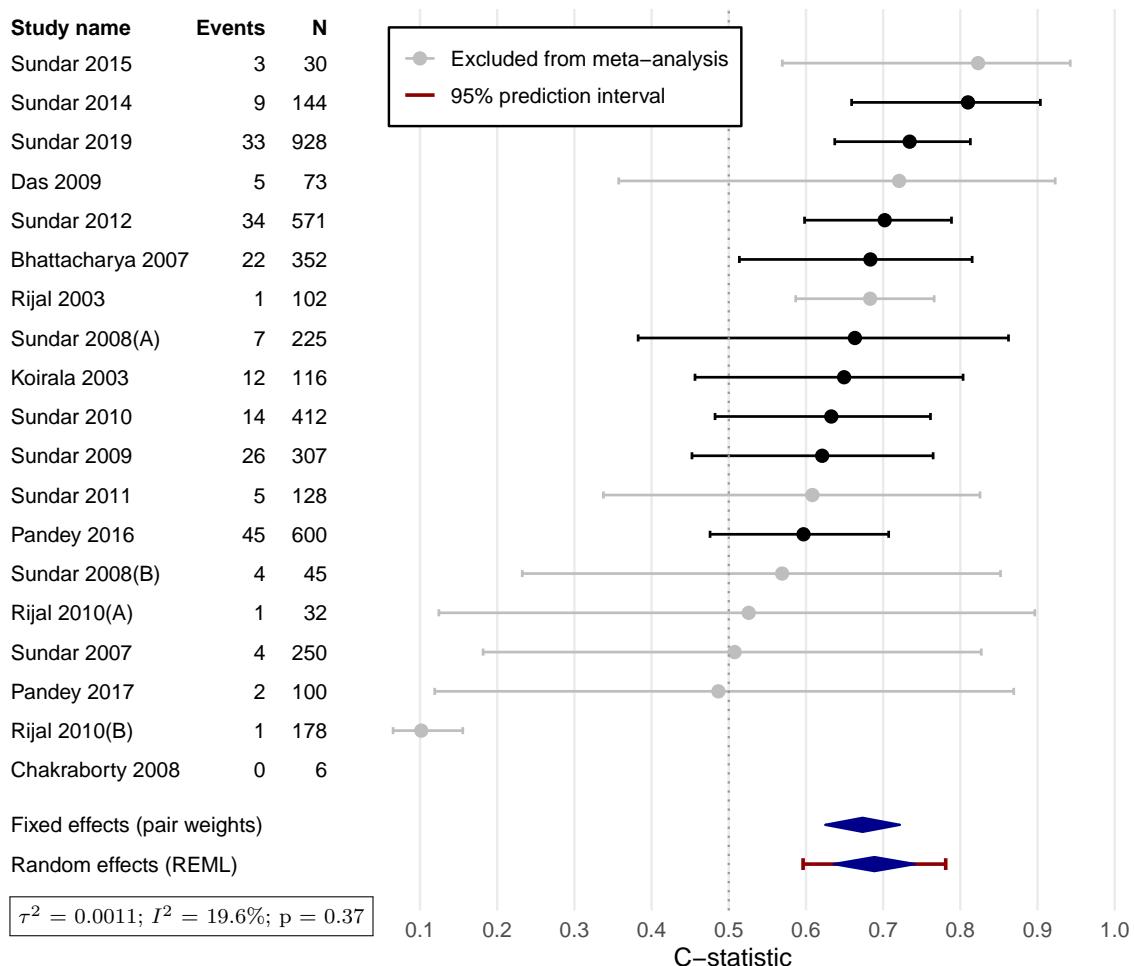


Figure C.18: Forest plot showing individual and pooled study c-statistics for the model **excluding** parasite grade. Pooled c-statistics are presented from both fixed-effects and random-effects meta-analysis models. Blue diamonds: pooled summary estimates with 95% confidence intervals. For Chakraborty 2008, no relapse events occurred and the c-statistic is therefore undefined. Study-specific confidence intervals should be interpreted with caution due to small sample sizes and relapse events in some studies (see Methodology Section 4.3.7).

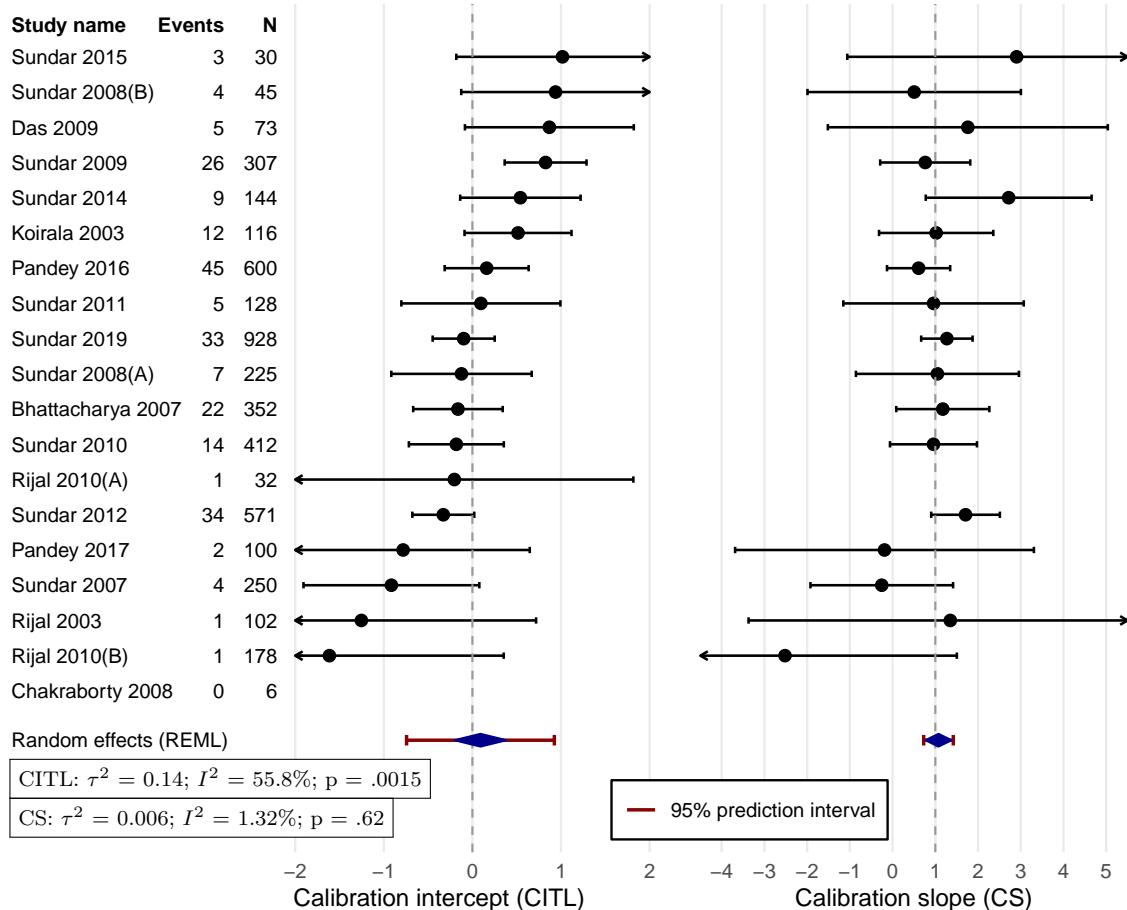


Figure C.19: Forest plots showing individual and pooled study calibration measures for the model **including** parasite grade. Left: calibration intercept (calibration-in-the-large, CITL); Right: calibration slope (CS). Blue diamonds: summary estimates with 95% confidence intervals. Calibration measures not presented for Chakraborty 2008 due to no relapse events. Calibration slope not presented for Rijal 2010(A) due to only one relapse event and few total participants leading to failure of model convergence.

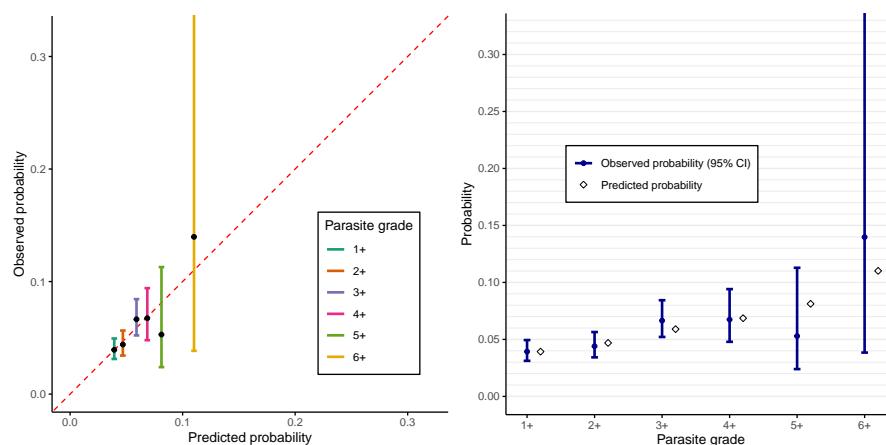


Figure C.20: Calibration plots for parasite grades — model **including** parasite grade.

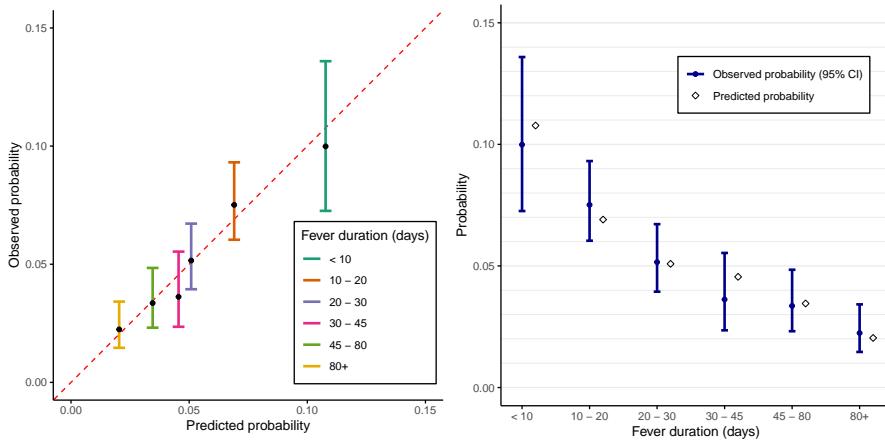


Figure C.21: Calibration plots for fever duration — model **including** parasite grade.

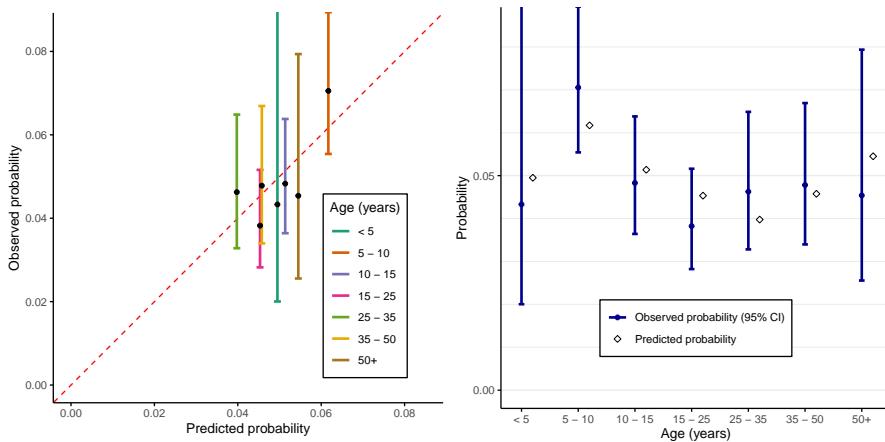


Figure C.22: Calibration plots for age — model **including** parasite grade.

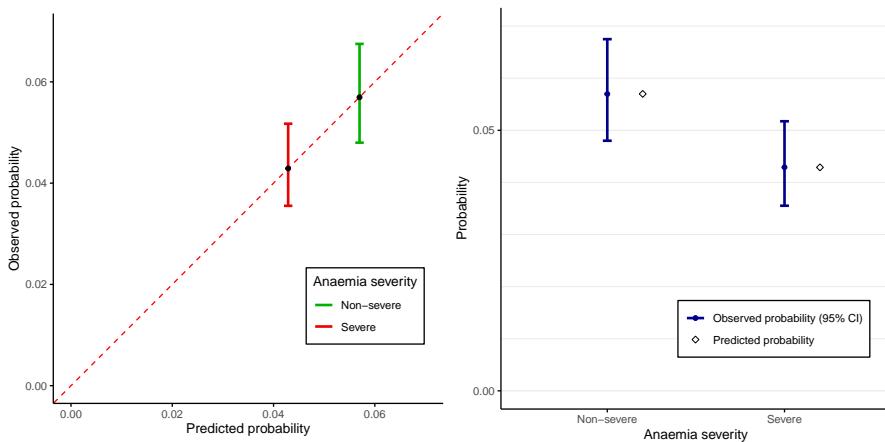


Figure C.23: Calibration plots for anaemia severity — model **including** parasite grade.

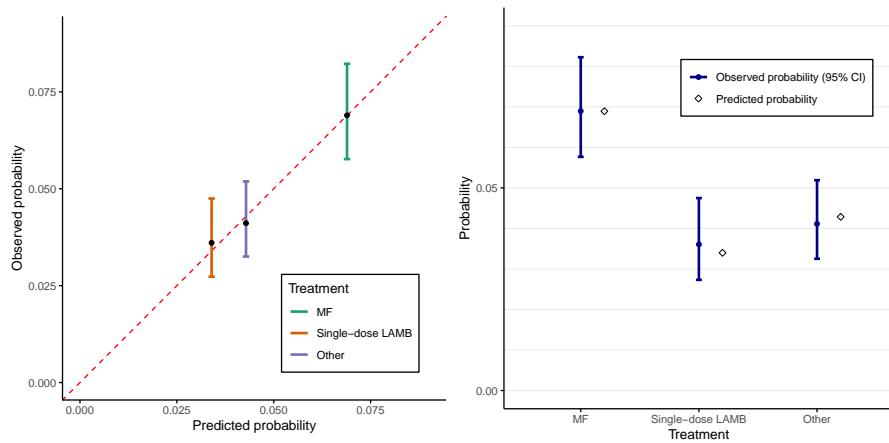


Figure C.24: Calibration plots for treatment — model **including** parasite grade.

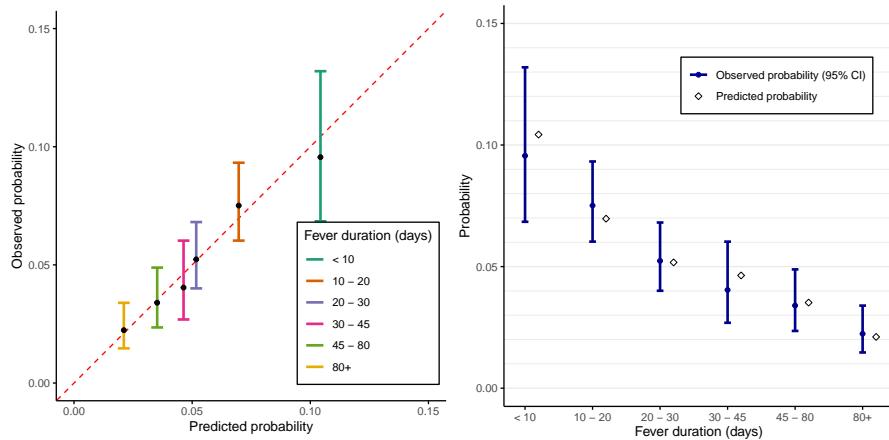


Figure C.25: Calibration plots for fever duration — model **excluding** parasite grade.

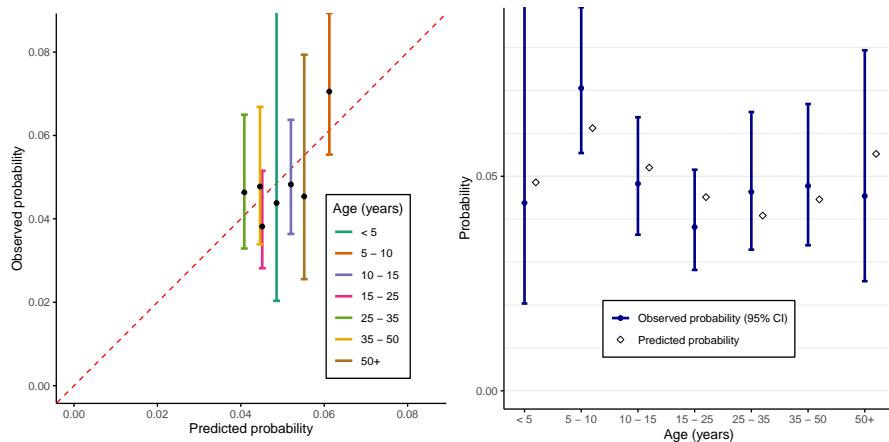


Figure C.26: Calibration plots for age — model **excluding** parasite grade.

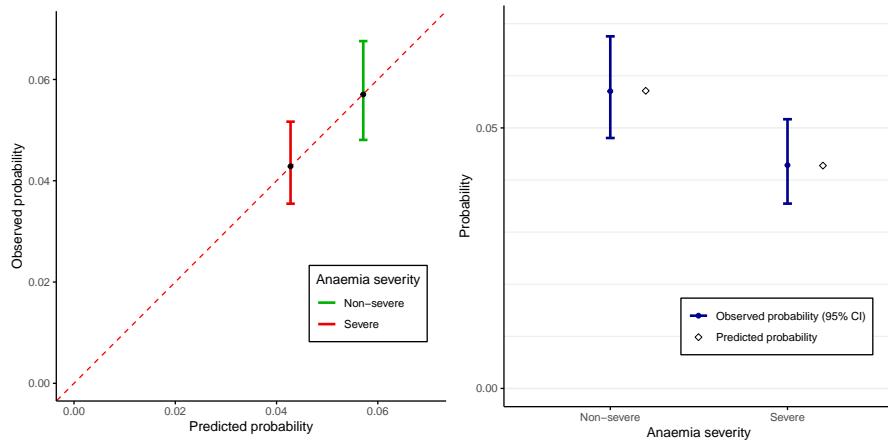


Figure C.27: Calibration plots for anaemia severity — model **excluding** parasite grade.

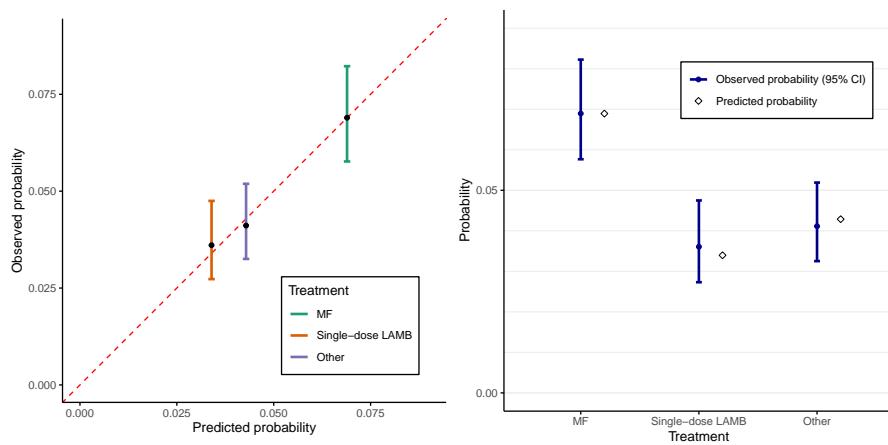


Figure C.28: Calibration plots for treatment — model **excluding** parasite grade.

D

Appendix — East Africa model results

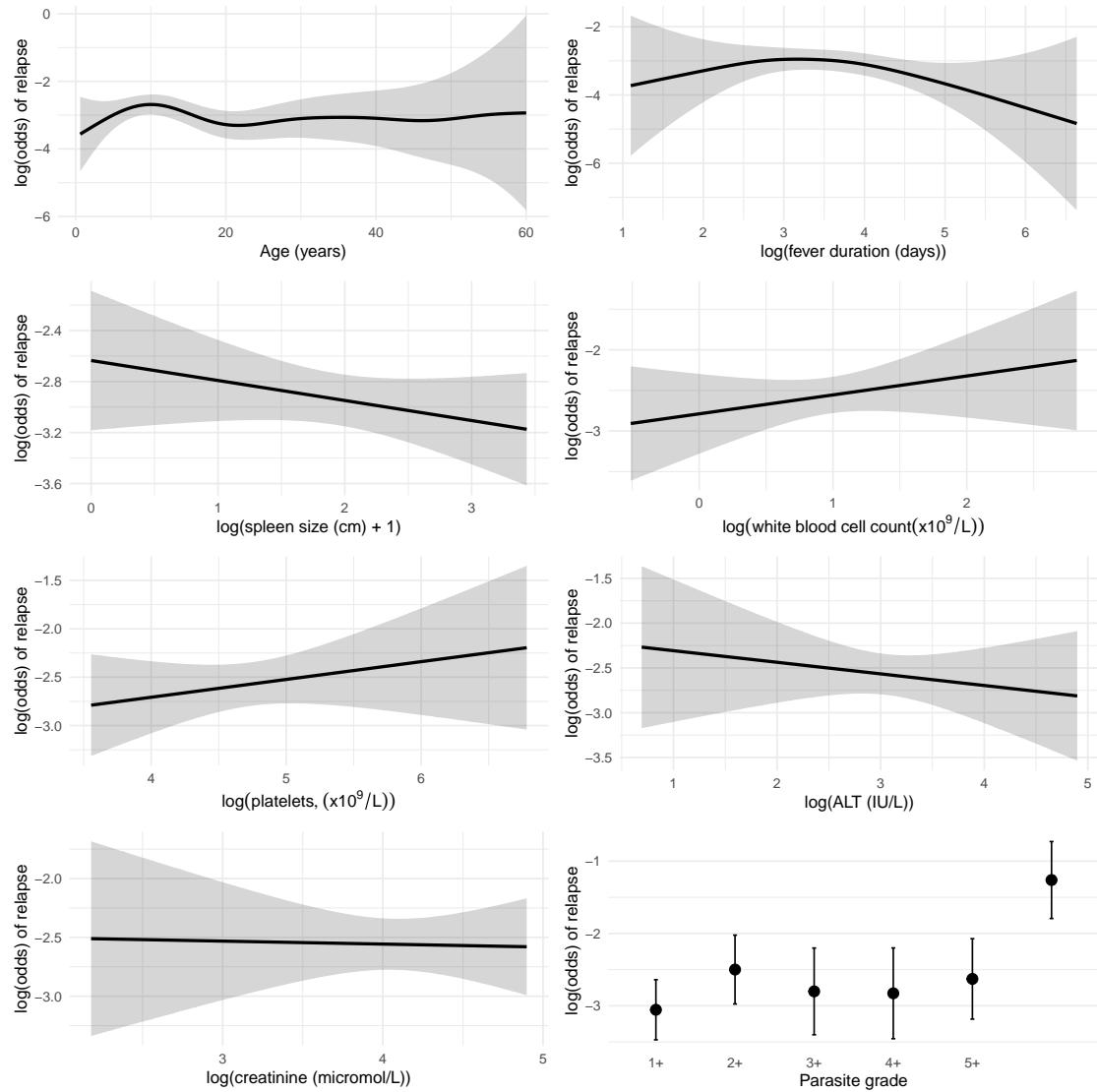


Figure D.1: Associations between transformed continuous predictors and $\log(\text{odds})$ of relapse. For each predictor (excluding parasite grade), a univariable generalised additive model spline fit is shown, with 95% confidence intervals. For parasite grade, 95% confidence intervals are calculated for each grade using the Wilson method.

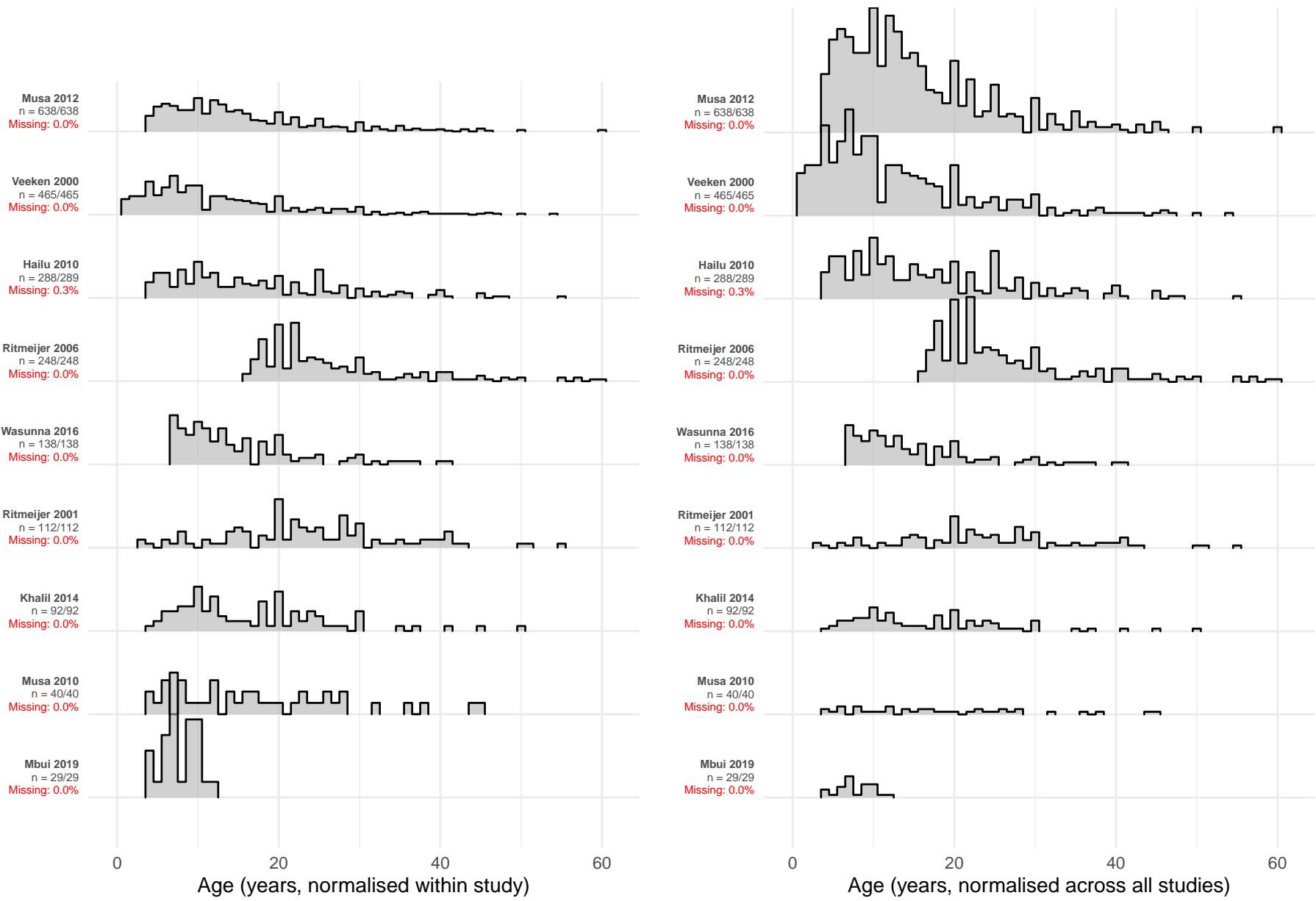


Figure D.2: Distribution of age across studies from East Africa. Missing age data described by study.

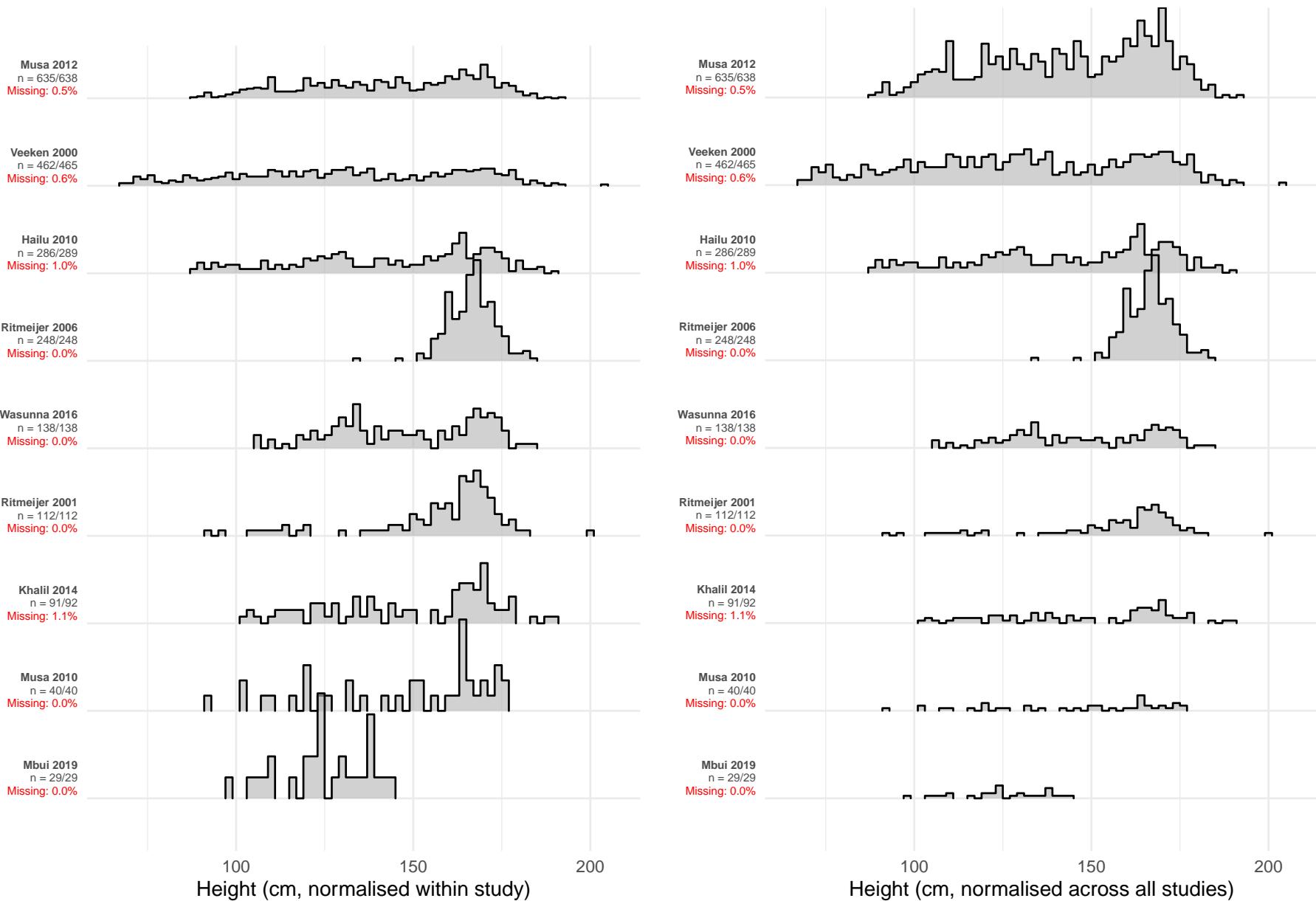


Figure D.3: Distribution of height across studies from East Africa. Missing data described by study.

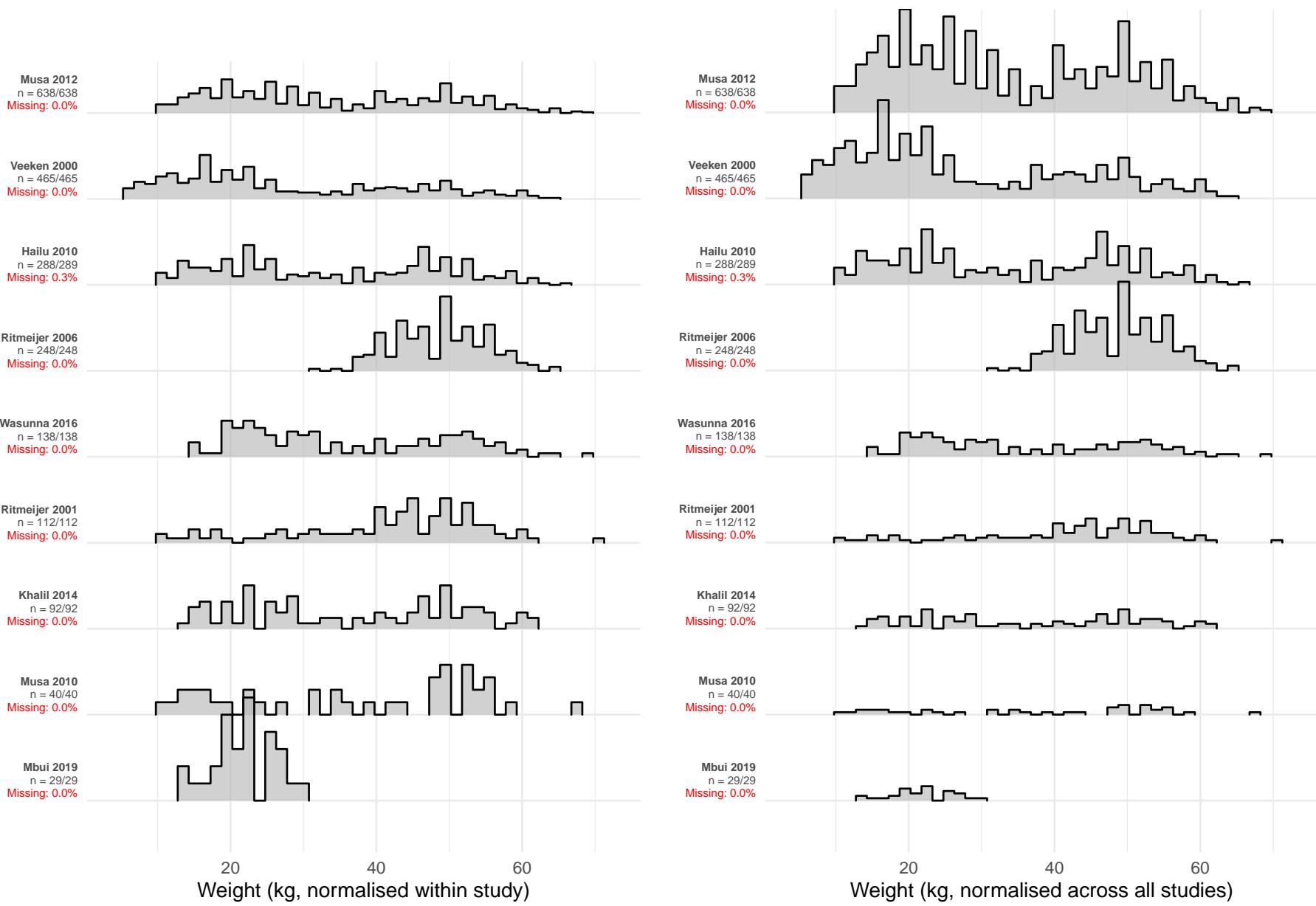


Figure D.4: Distribution of weight across studies from East Africa. Missing data described by study.

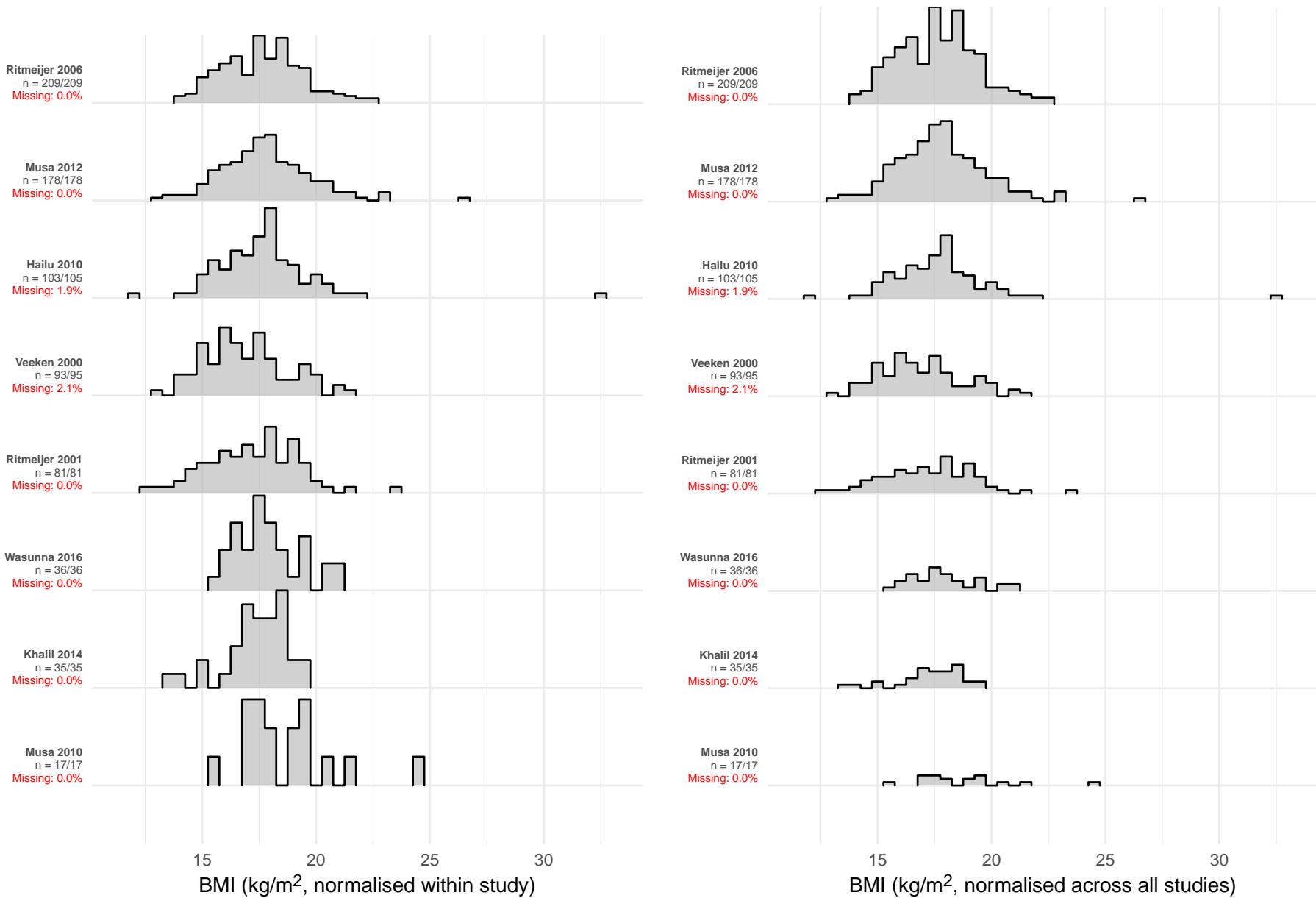


Figure D.5: Distribution of BMI across studies from East Africa. Including only participants aged 19 and over (Pandey 2017 excluded). Missing data described by study.

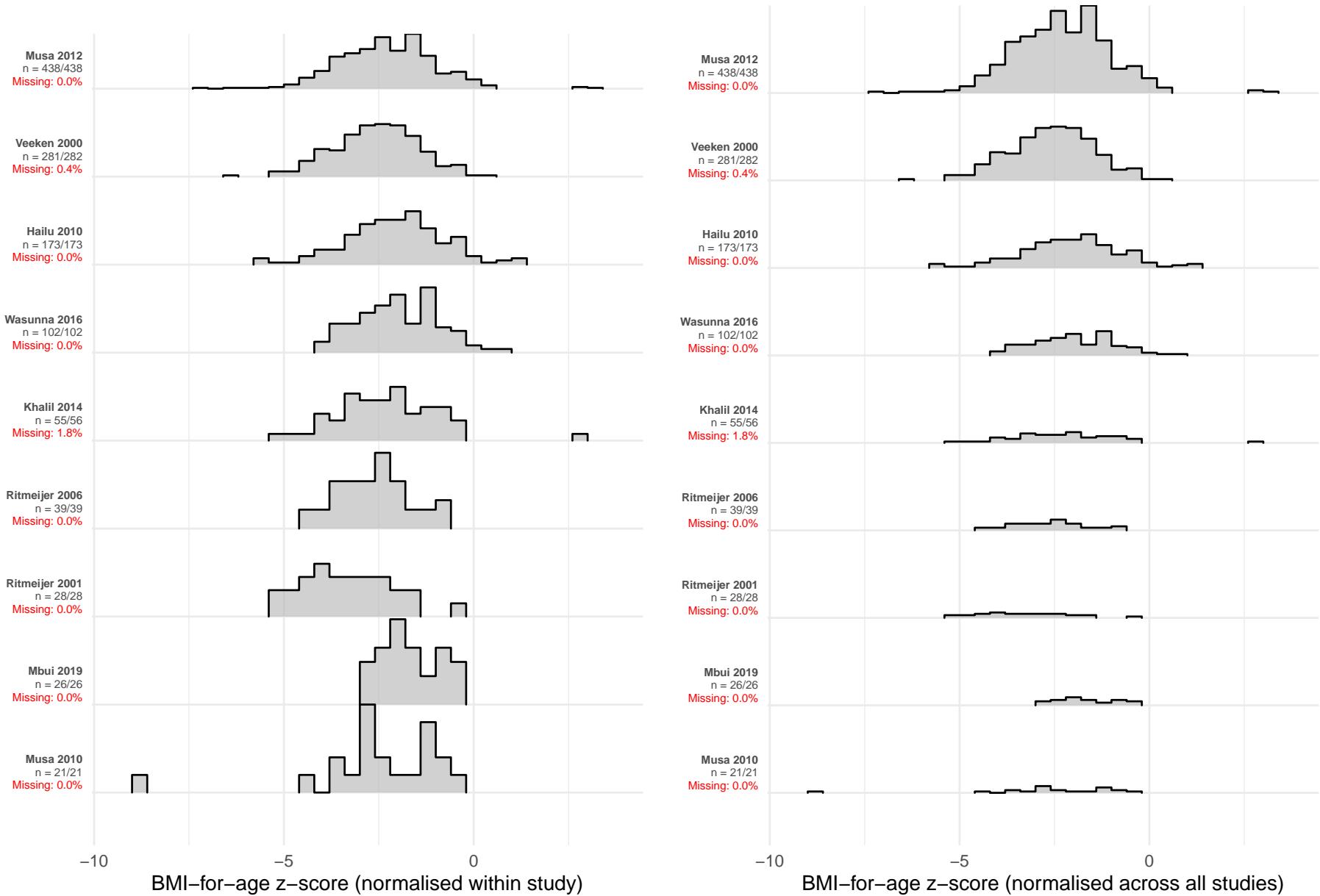


Figure D.6: Distribution of BMI-for-age z score across studies from East Africa. Including only participants aged from 5–18, inclusive. Missing data described by study.

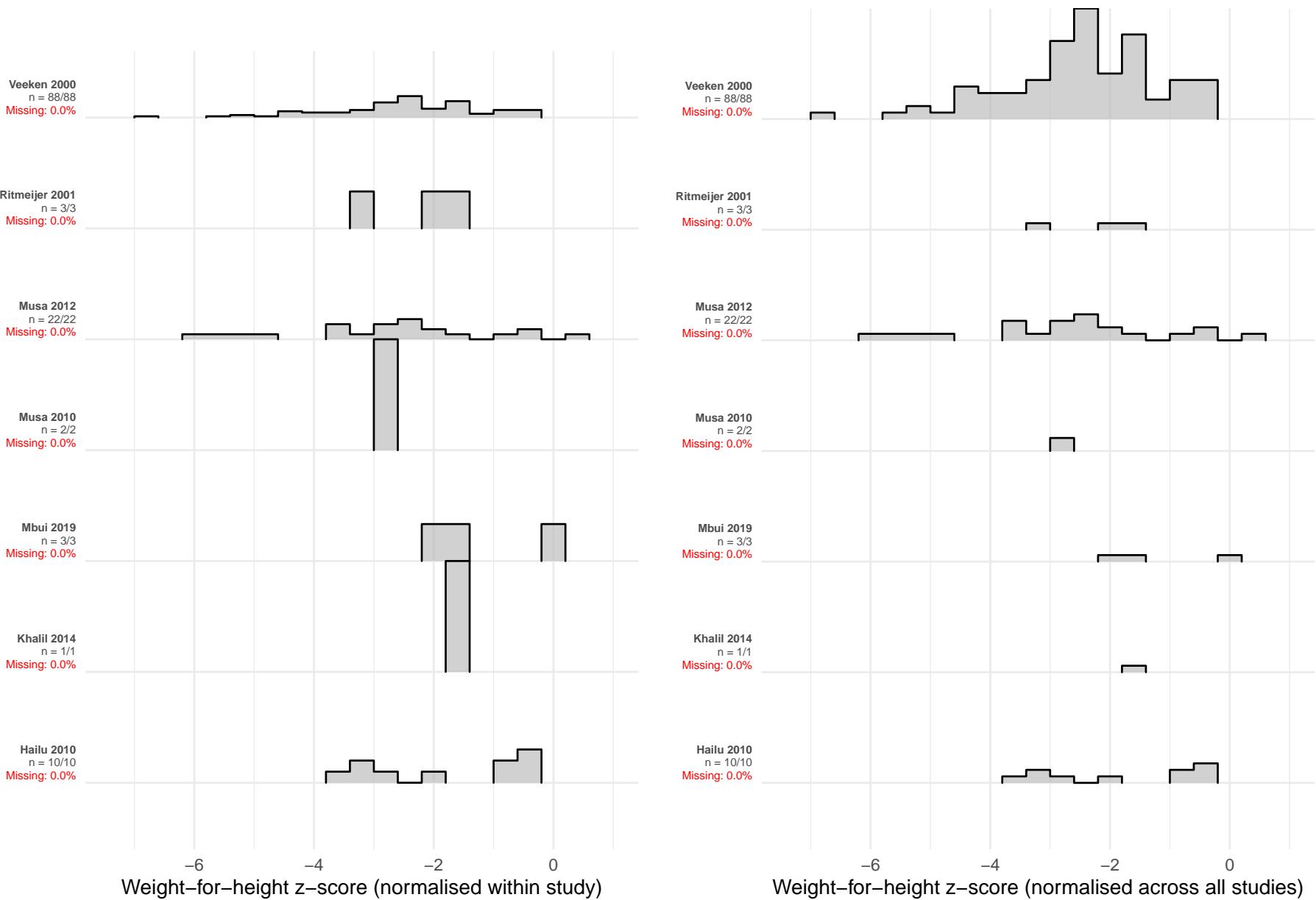


Figure D.7: Distribution of weight-for-height z score across studies from East Africa. Including only participants aged under 5. Missing data described by study.

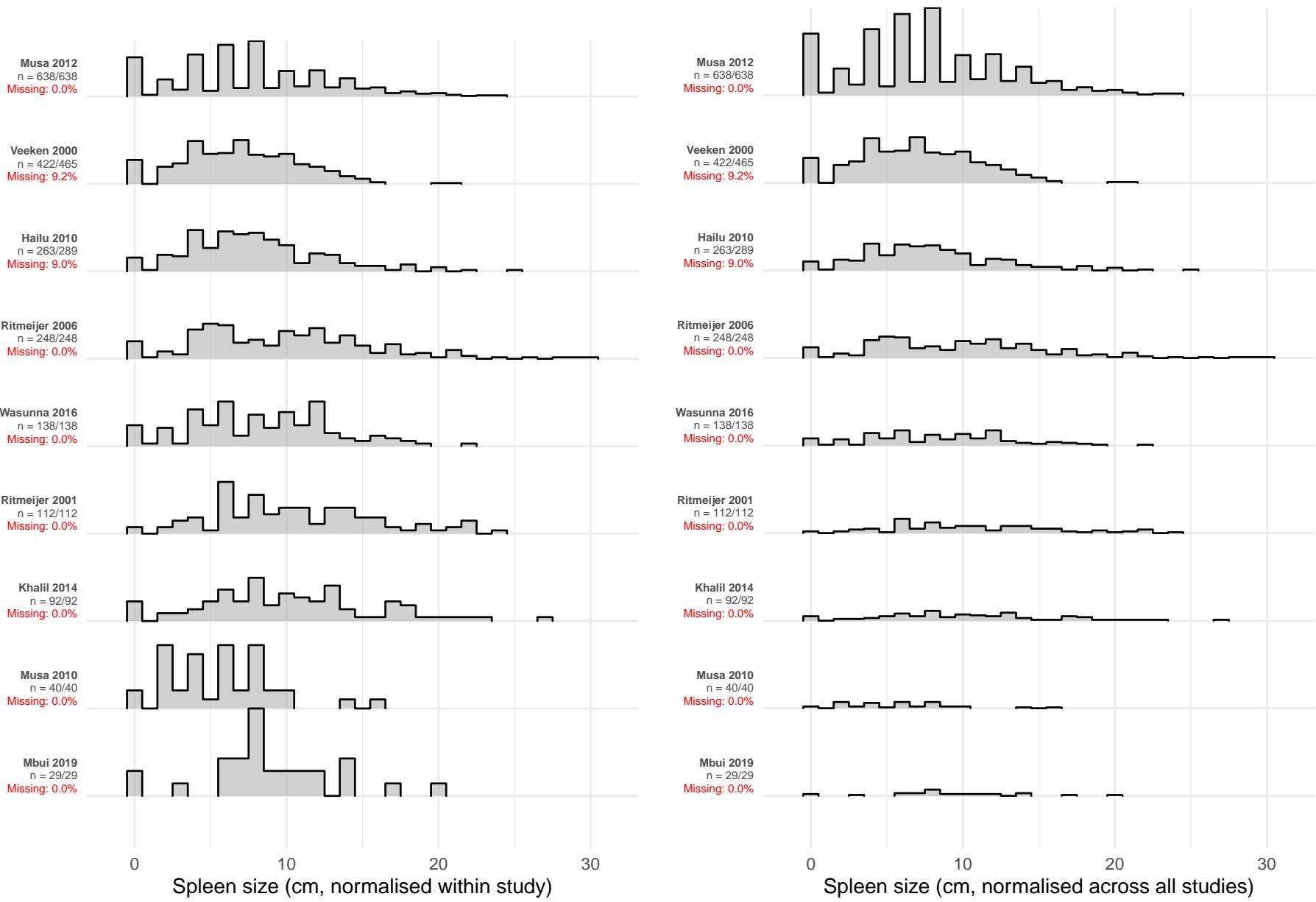


Figure D.8: Distribution of spleen size across studies from East Africa. Missing data described by study.

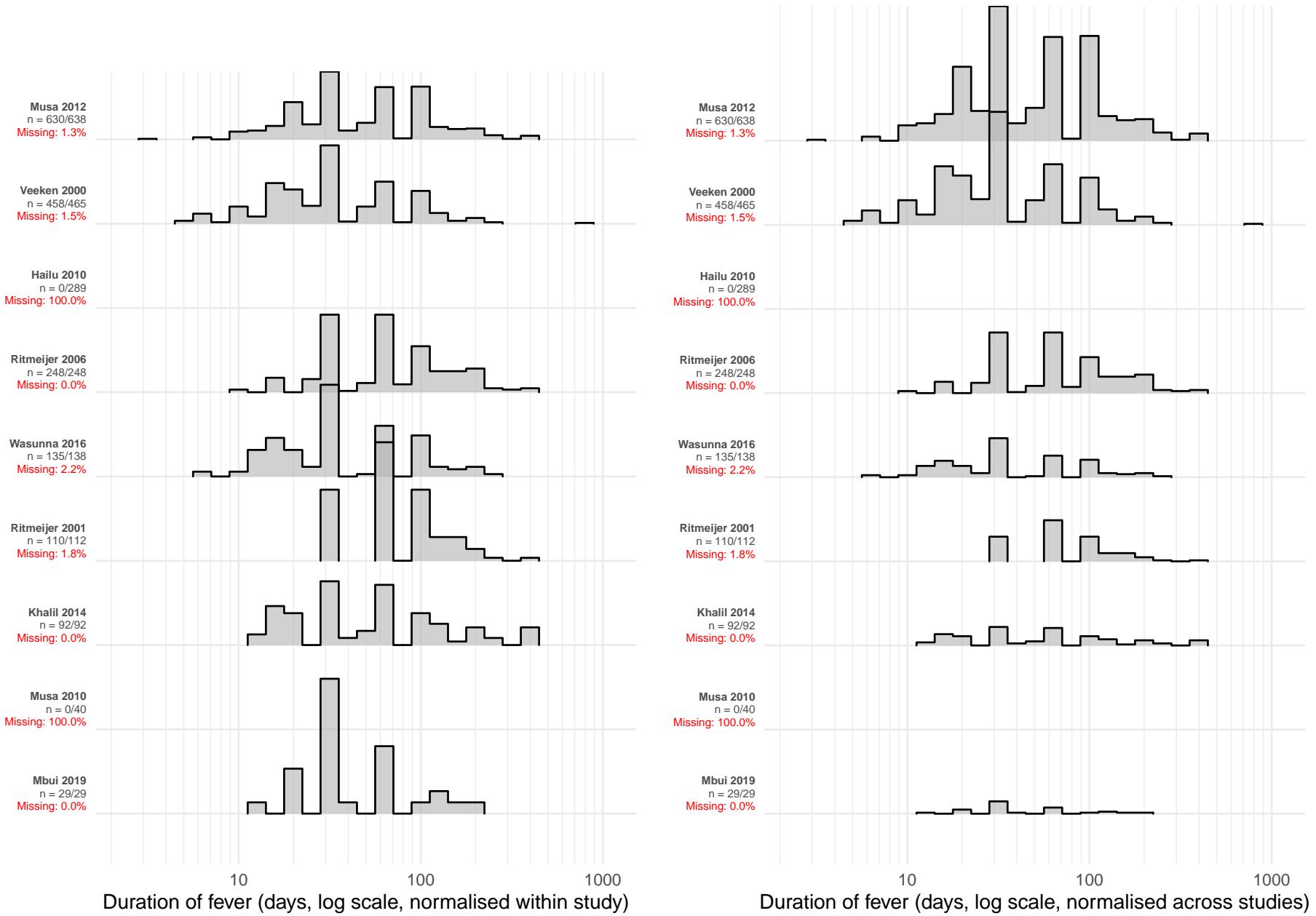


Figure D.9: Distribution of fever duration (log scale) across studies from East Africa. Missing data described by study.

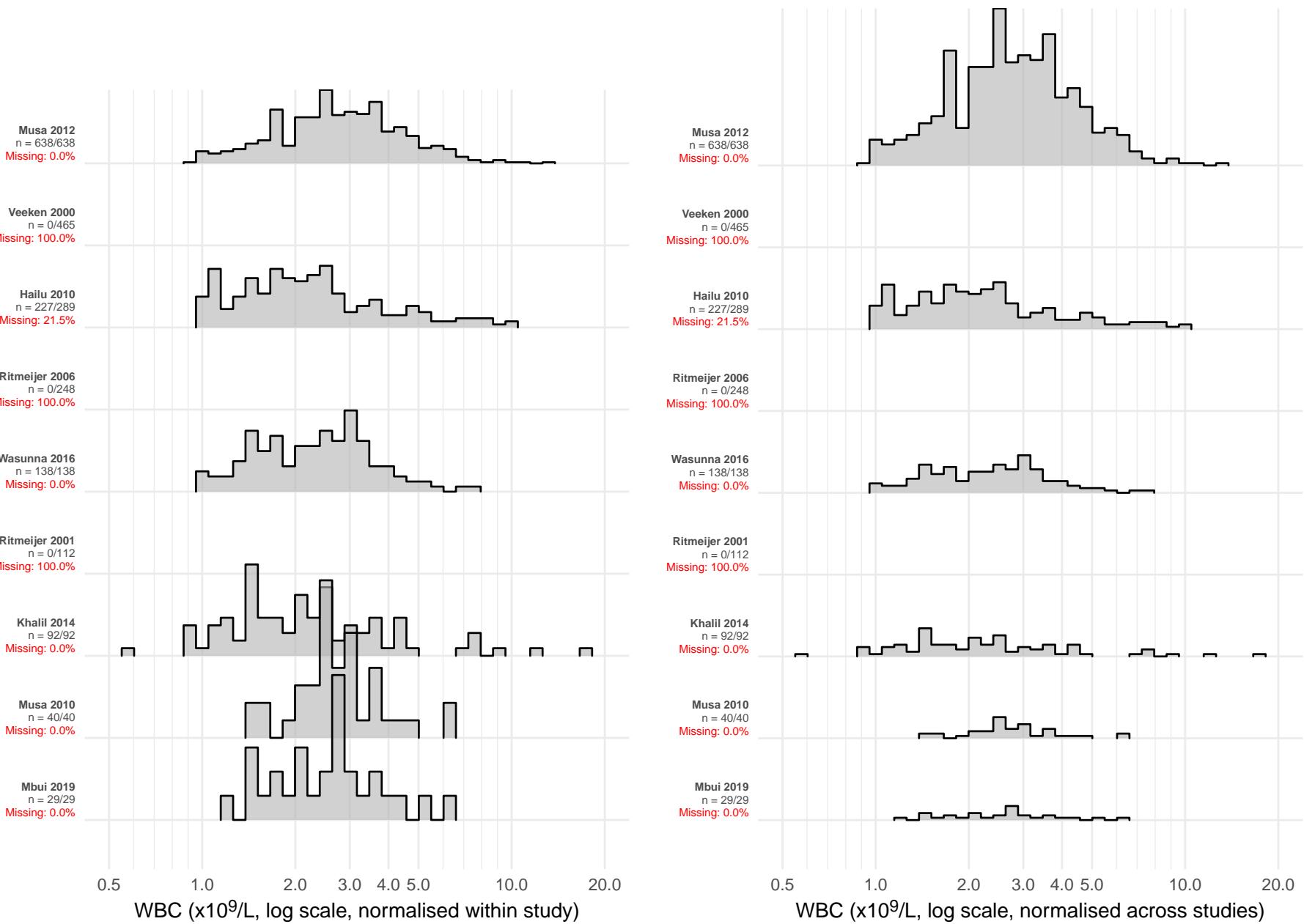


Figure D.10: Distribution of white blood cell count (log scale) across studies from East Africa. Missing data described by study.

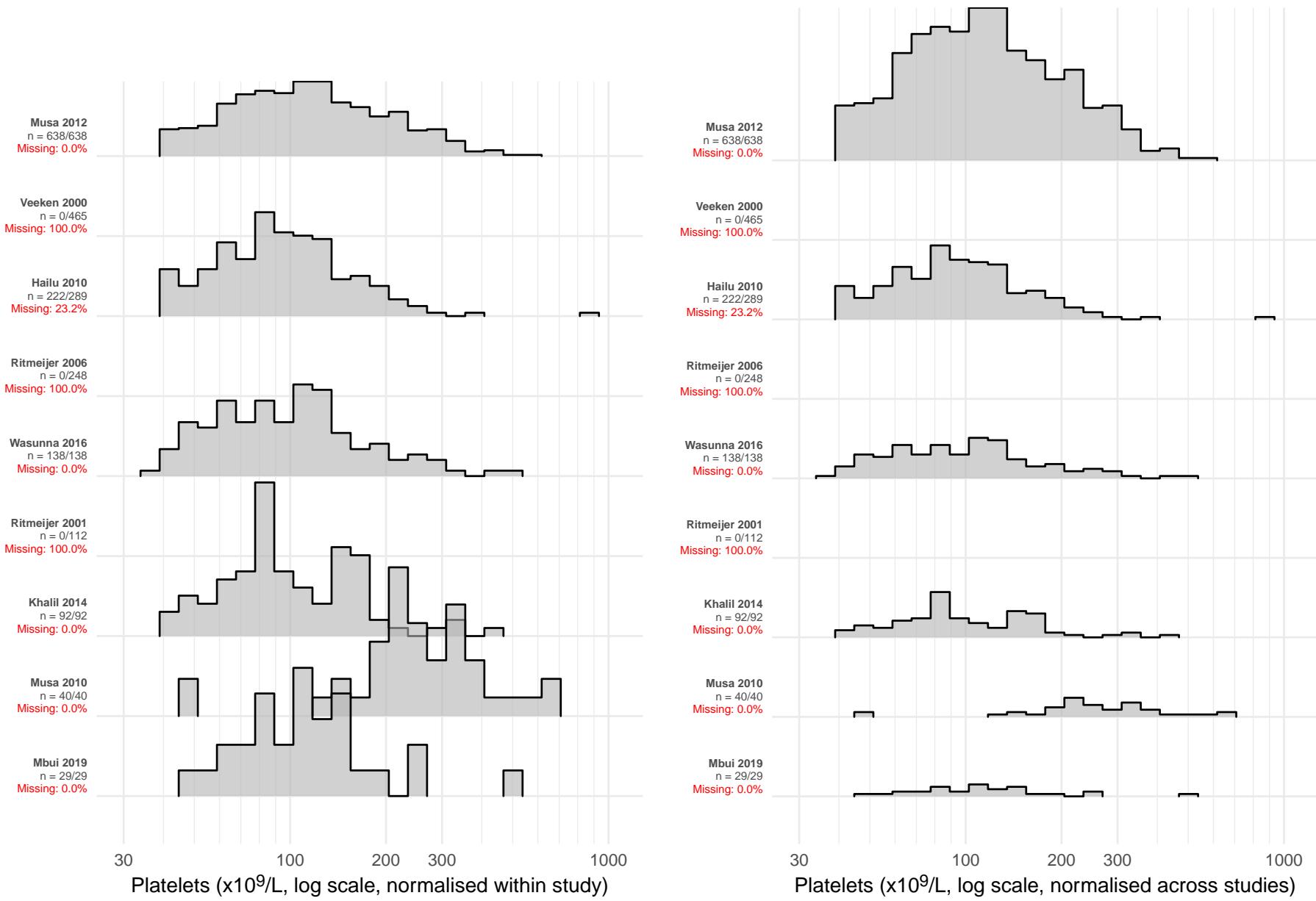


Figure D.11: Distribution of platelet count (log scale) across studies from East Africa. Missing data described by study.

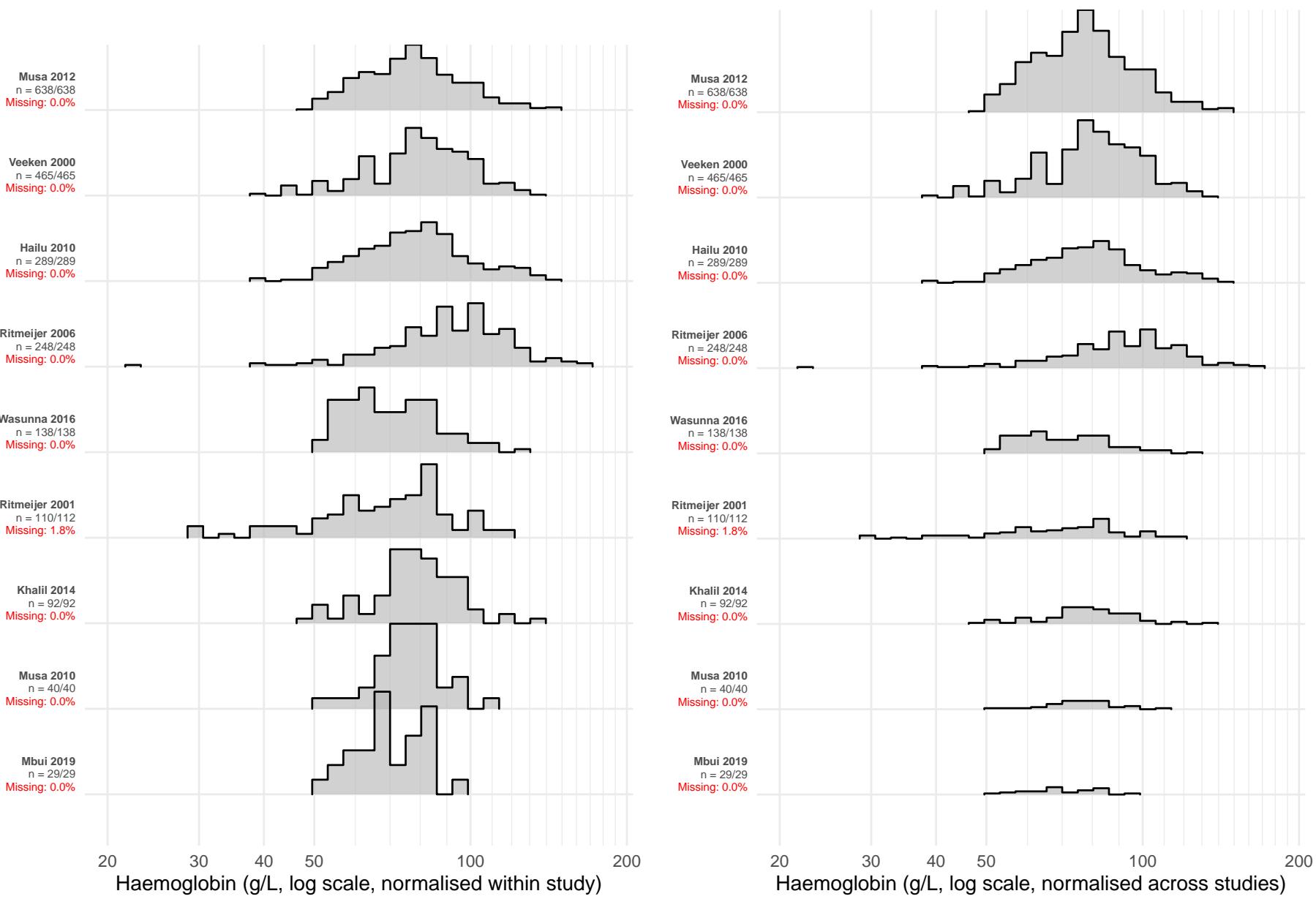


Figure D.12: Distribution of haemoglobin (log scale) across studies from East Africa. Missing data described by study.

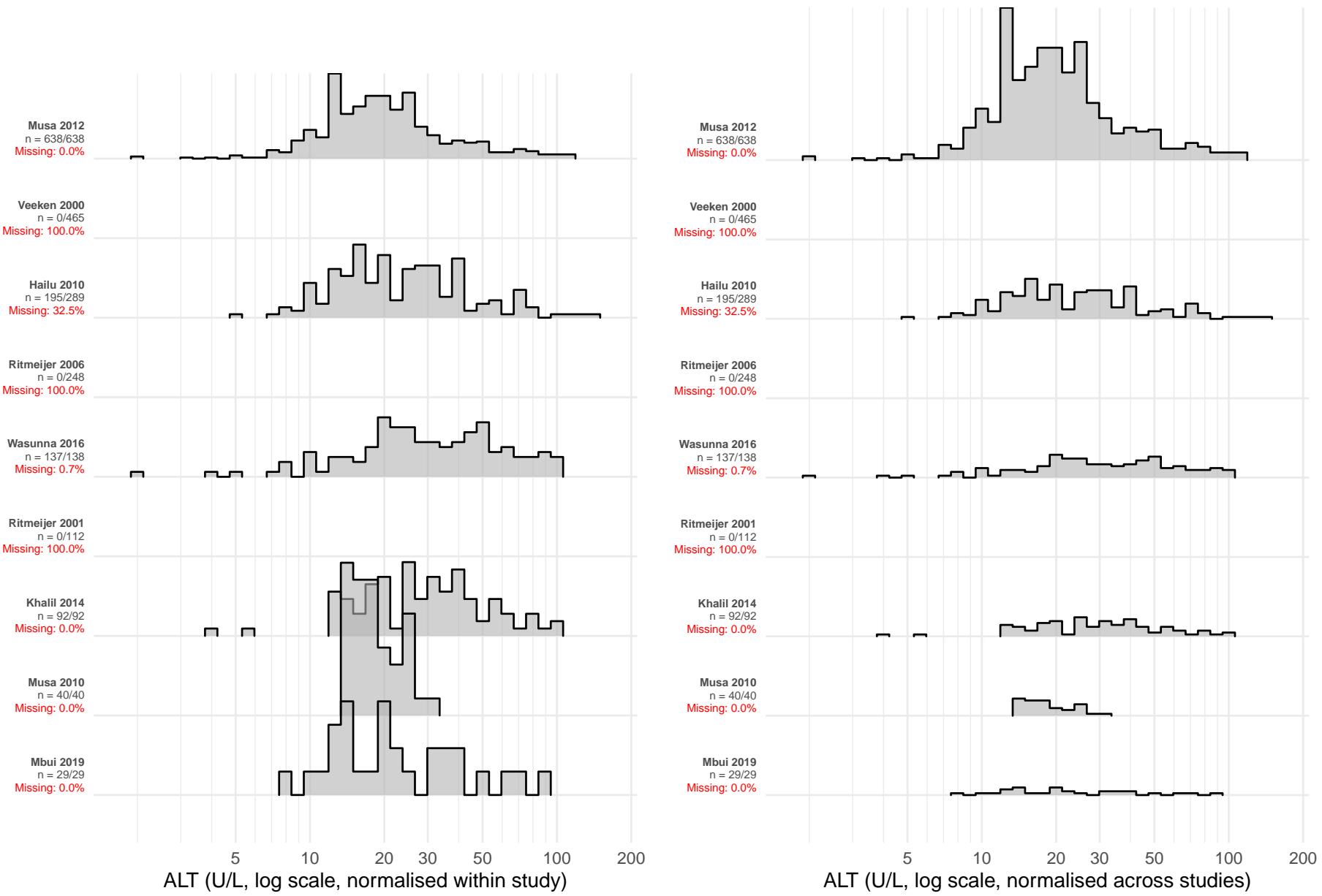


Figure D.13: Distribution of alanine transaminase (ALT, log scale) across studies from East Africa. Missing data described by study.

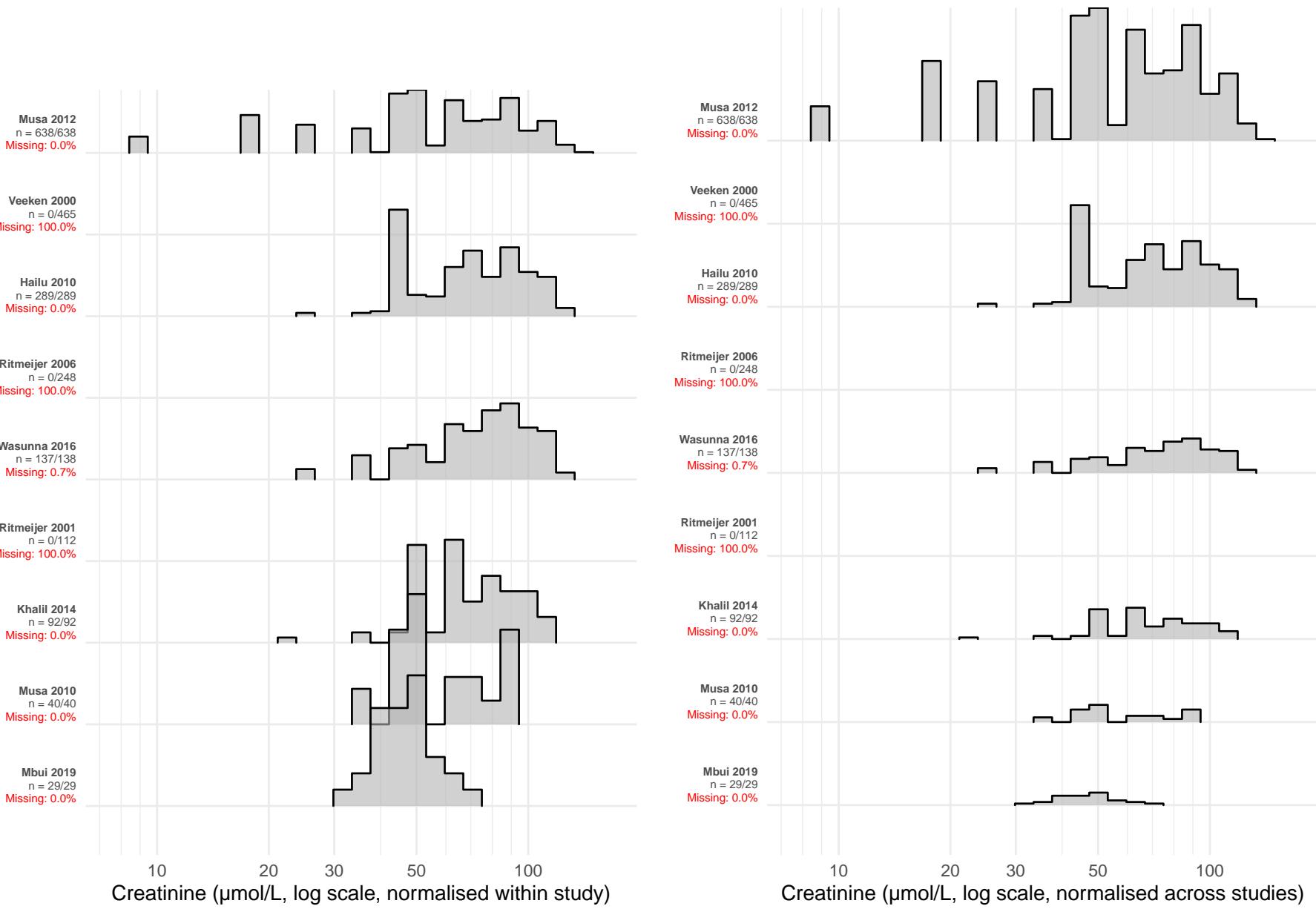


Figure D.14: Distribution of creatinine (log scale) across studies from East Africa. Missing data described by study.

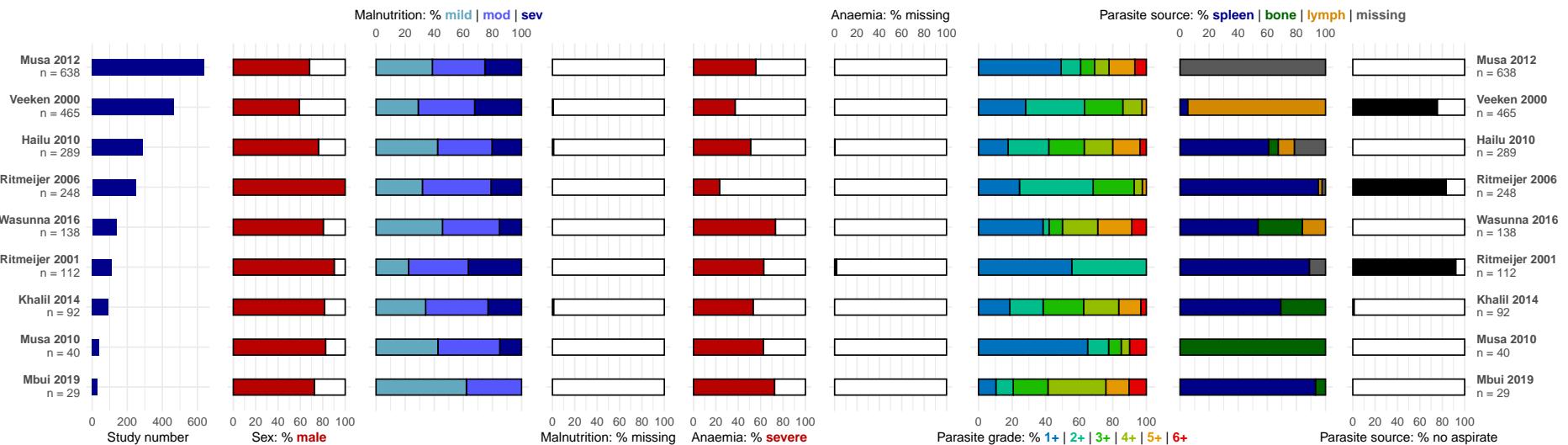


Figure D.15: Distribution of categorical predictors by study. Missing data excluded from stacked bar charts, except for parasite source, where ‘missing’ refers to patients where aspirates were performed, but aspirate source not available.

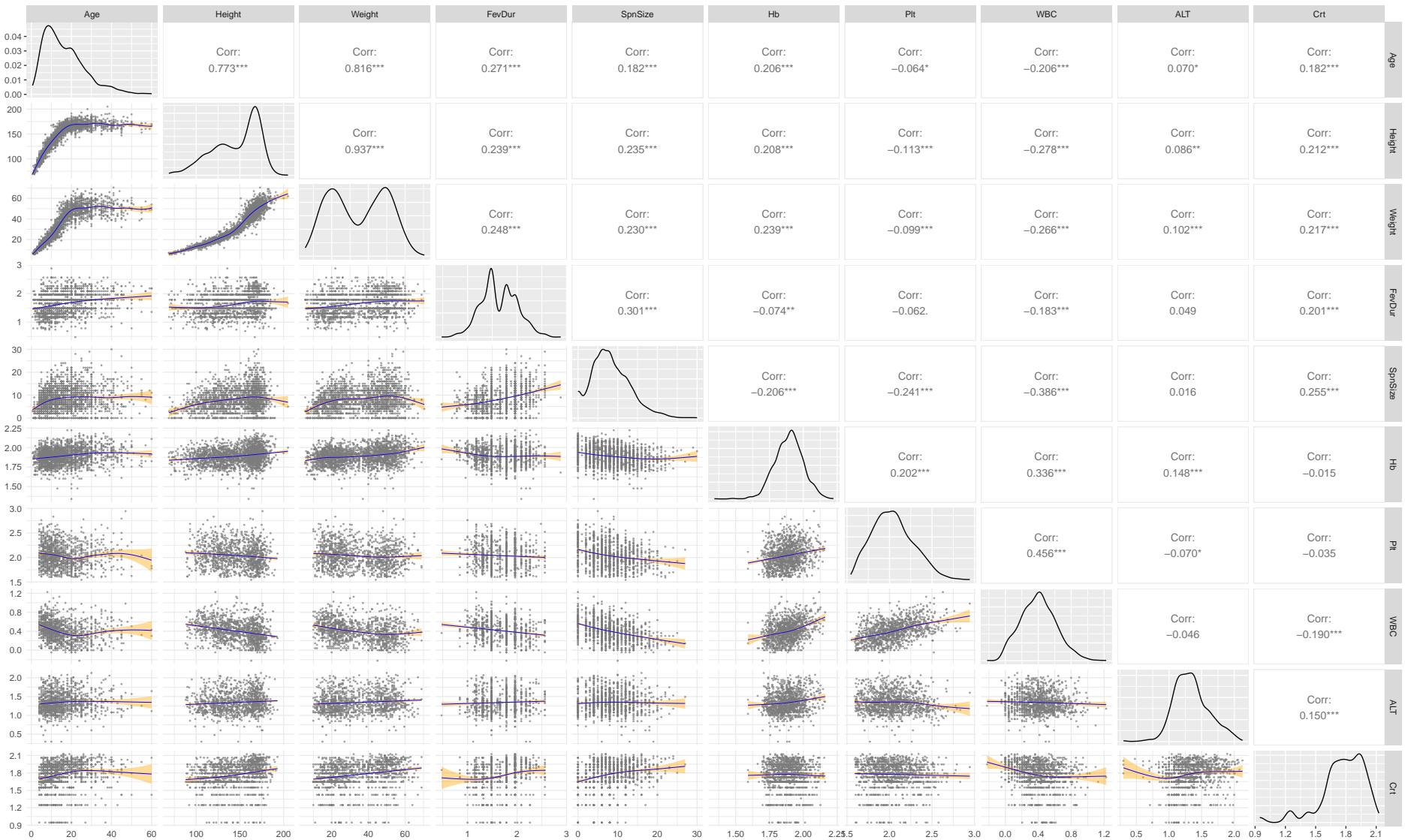


Figure D.16: Correlation between continuous variables. For scatter plots, a univariable generalised additive model is fitted (blue line) with 95% confidence interval ribbon filled (orange area). Pearson correlation coefficients are presented, *** p<0.001; ** p<0.01; * p<0.05, . p<0.10. Age: years; Height: cm; Weight: kg; FevDur: duration of fever, log10(days); SpnSize: spleen size (cm); Hb: haemoglobin, log10(g/L); Plt: platelets, log10($\times 10^9/L$); WBC: white blood cells log10($\times 10^9/L$); ALT: alanine aminotransferase, log10(U/L); Cr: creatinine log10($\mu\text{mol}/L$).

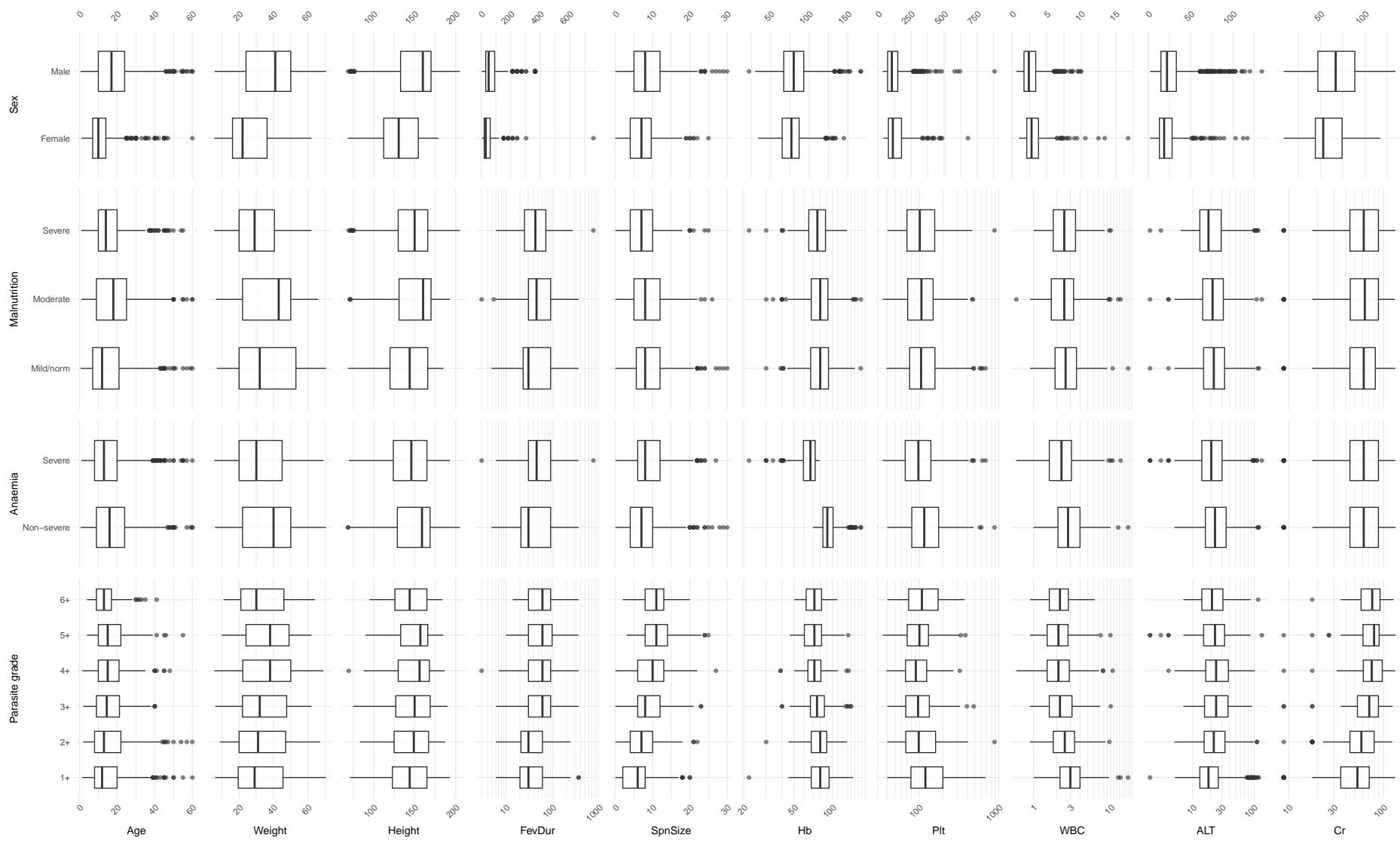


Figure D.17: Correlation between continuous and categorical variables. FevDur and laboratory tests axes transformed to log₁₀ scale. Age: years; Height: cm; Weight: kg; FevDur: duration of fever, days; SpnSize: spleen size, cm; Hb: haemoglobin, g/L; Plt: platelets, $\times 10^9/L$; WBC: white blood cells $\times 10^9/L$; ALT: alanine aminotransferase, U/L; Cr: creatinine $\mu\text{mol}/L$.

term	estimate ¹	std.error	t statistic	df (effective)	p value
Fixed intercept	-3.7874	0.5369	-7.05	1885.50	2.43E-12
Parasite grade ²	0.3593	0.0763	4.71	1044.63	2.83E-06
Spleen size ³	-0.3335	0.1741	-1.92	1813.86	5.56E-02
Anaemia: Severe ⁴	0.5450	0.2448	2.23	1973.14	2.61E-02
Fever duration ⁵	-0.3302	0.1349	-2.45	476.32	1.47E-02
WBC count ⁶	0.2368	0.1315	1.80	419.77	7.23E-02
Malnutrition: Moderate ⁷	0.5769	0.2677	2.16	2004.45	3.13E-02
Malnutrition: Severe ⁷	0.9780	0.2860	3.42	2025.03	6.39E-04
Unadjusted intercept (Musa 2012):	-3.9411				
Uniform shrinkage factor:	0.8079				
Adjusted intercepts after shrinkage: Average:	-4.3182; Musa 2012:	-4.4524			
Pooled τ^2 :	0.9122.	Pooled ICC:	0.2169		

¹ Logit scale before uniform shrinkage.

² Continuous variable, from 1+ to 6+ as described by Chulay and Bryceson[51]. Transformed $x \mapsto x - 1$.

³ Units: centimetres. Converted to natural log scale $x \mapsto \log(x + 1)$.

⁴ Reference group: non-severe anaemia.

⁵ Units: days. Converted to natural log scale and then standardised by mean (3.550509) and standard deviation (0.8693318).

⁶ Units: $\times 10^9$ cells per litre. Converted to natural log scale and then standardised by mean (0.926133) and standard deviation (0.4911651).

⁷ Reference group: Mild/normal malnutrition.

Table D.1: Model coefficients pooled across 30 imputed datasets using Rubin's Rules.

Model **including** parasite grade. df: degrees of freedom; std.error: standard error; WBC: white blood cell count

term	estimate ¹	std.error	t statistic	df (effective)	p value
Fixed intercept	-3.7674	0.4381	-8.60	2028.60	1.57E-17
Anaemia: Severe ²	0.5553	0.2365	2.35	1981.61	1.89E-02
WBC count ³	0.2254	0.1167	1.93	715.01	5.39E-02
Malnutrition: Moderate ⁴	0.5486	0.2625	2.09	2002.50	3.67E-02
Malnutrition: Severe ⁴	0.9282	0.2794	3.32	2017.72	9.08E-04
Unadjusted intercept (Musa 2012): -3.9073					
Uniform shrinkage factor: 0.7493					
Adjusted intercepts after shrinkage: Average: -4.4889; Musa 2012: -4.6065					
Pooled τ^2 : 1.040. Pooled ICC: 0.2401					

¹ Logit scale before uniform shrinkage.

² Reference group: non-severe anaemia.

³ Units: $\times 10^9$ cells per litre. Converted to natural log scale and then standardised by mean (0.926133) and standard deviation (0.4911651).

⁴ Reference group: Mild/normal malnutrition.

Table D.2: Model coefficients pooled across 30 imputed datasets using Rubin's Rules. Model **excluding** parasite grade. df: degrees of freedom; std.error: standard error; WBC: white blood cell count

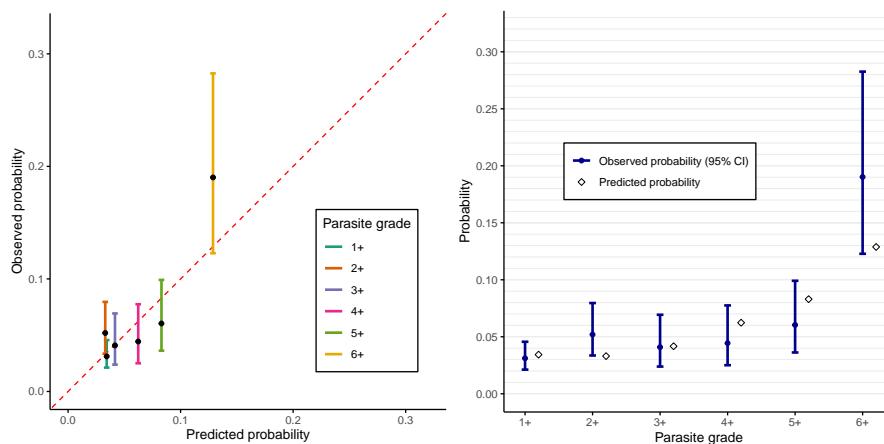


Figure D.18: Calibration plots for parasite grades — model **including** parasite grade.

Predictors	Model with PG	Model without PG
Parasite grade	499¹	n/a
Malnutrition	477¹	461¹
Fever duration	390¹	176
Anaemia	298¹	361¹
Spleen size	281¹	84
WBC count	254¹	188¹
Age (linear)	205	209
Creatinine	194	101
Age (squared)	162	161
ALT	137	138
Sex	124	119
Age (cubic)	57	71
Platelets	55	53

¹ Selected in final model.

Table D.3: Frequency of predictor selection during 500 bootstrap model developments. Predictors sorted by selection frequency in the model with parasite grade. ALT: alanine aminotransferase; n/a: not applicable; PG: parasite grade; WBC: white blood cell count

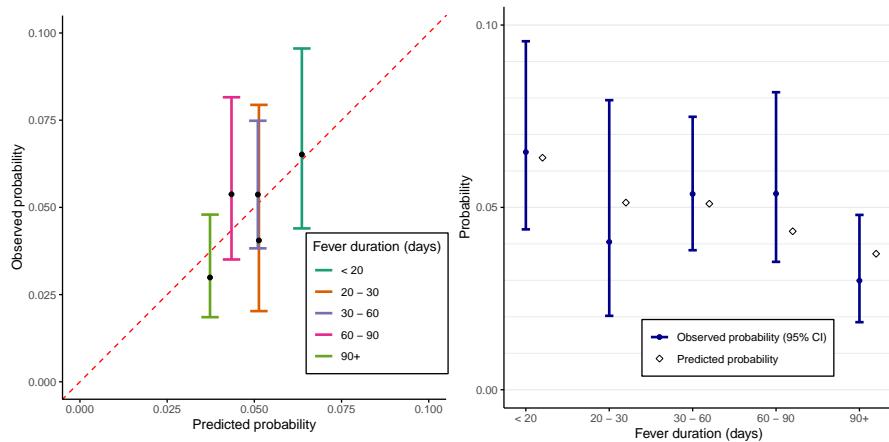


Figure D.19: Calibration plots for fever duration — model **including** parasite grade.

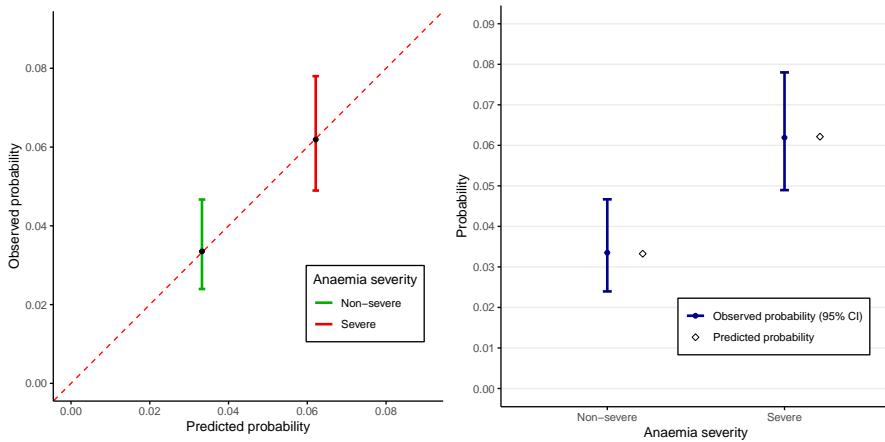


Figure D.20: Calibration plots for anaemia — model **including** parasite grade.

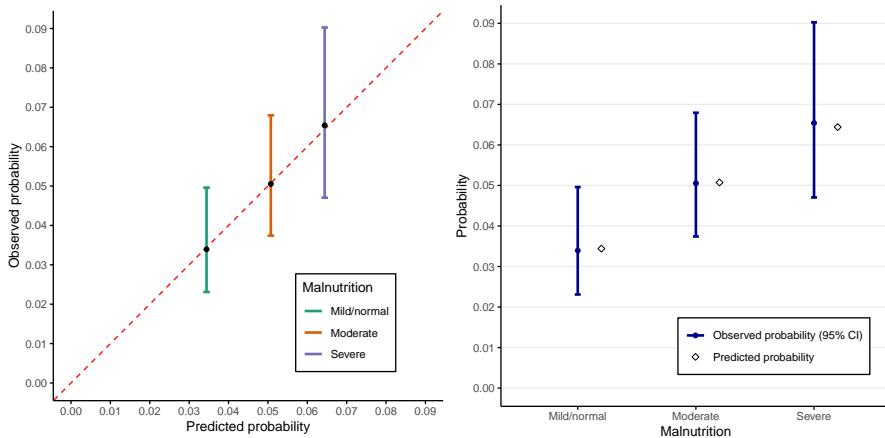


Figure D.21: Calibration plots for malnutrition — model **including** parasite grade.

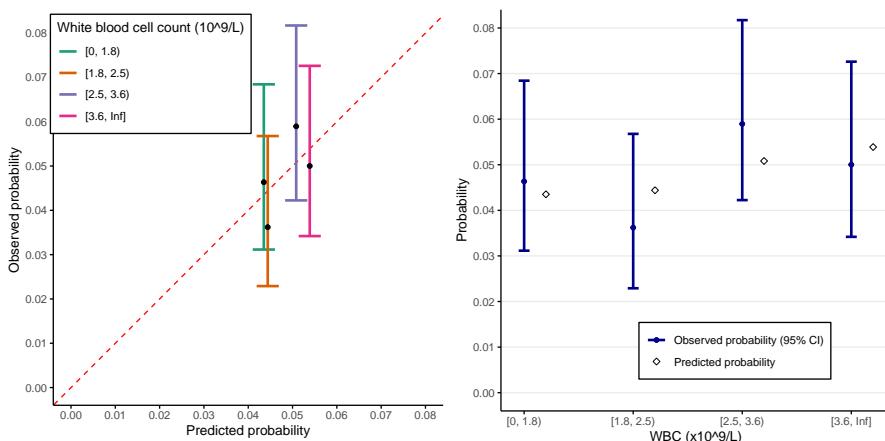


Figure D.22: Calibration plots for white blood cell count — model **including** parasite grade.

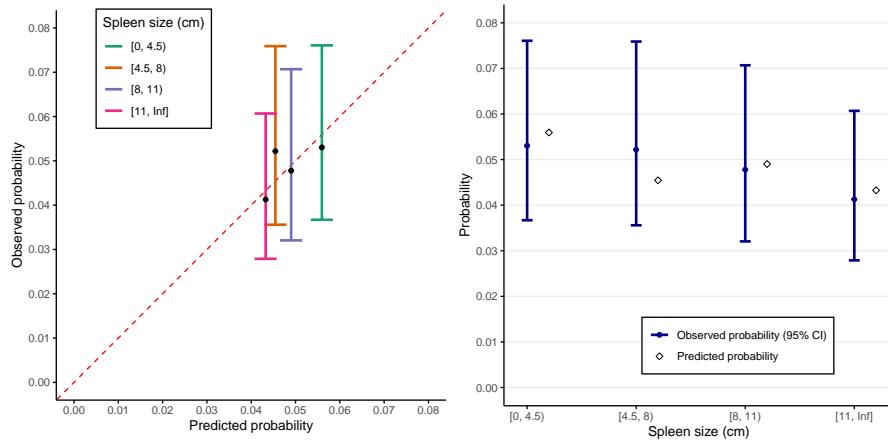


Figure D.23: Calibration plots for spleen size — model **including** parasite grade.

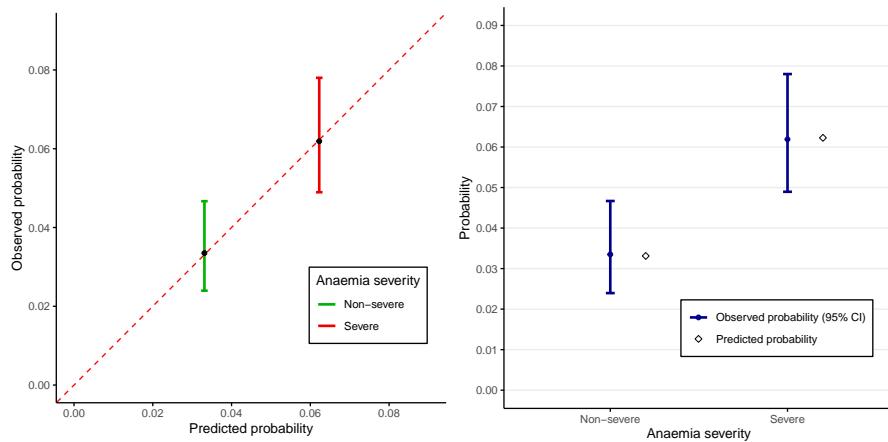


Figure D.24: Calibration plots for anaemia — model **excluding** parasite grade.

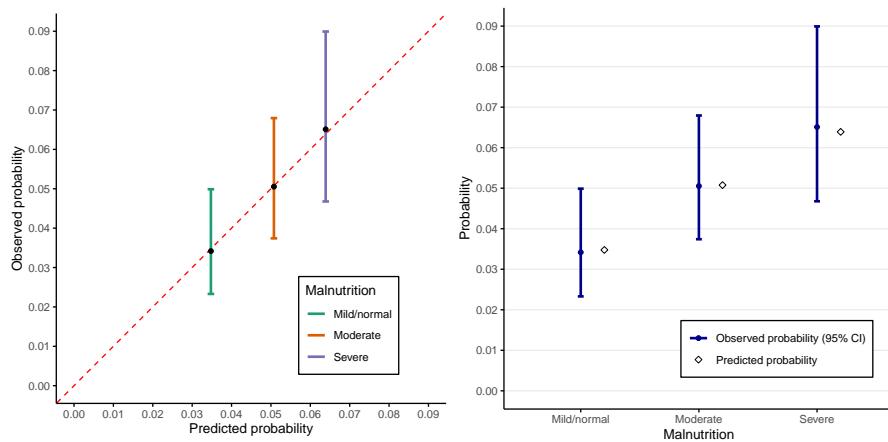


Figure D.25: Calibration plots for malnutrition — model **excluding** parasite grade.

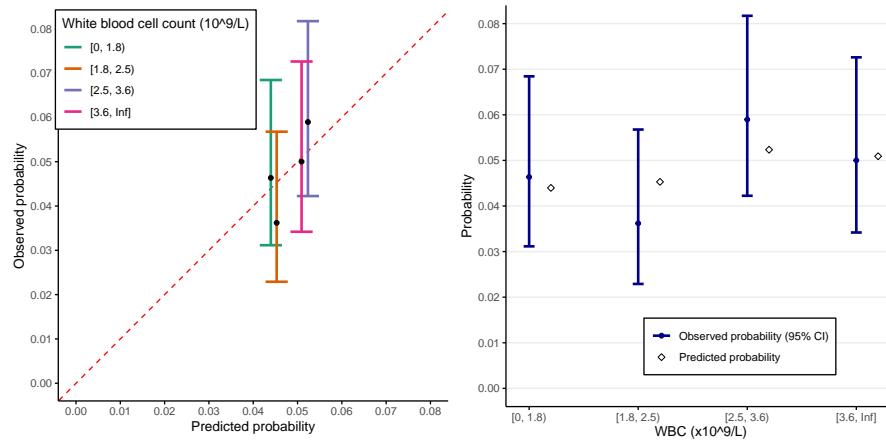


Figure D.26: Calibration plots for white blood cell count — model **excluding** parasite grade.

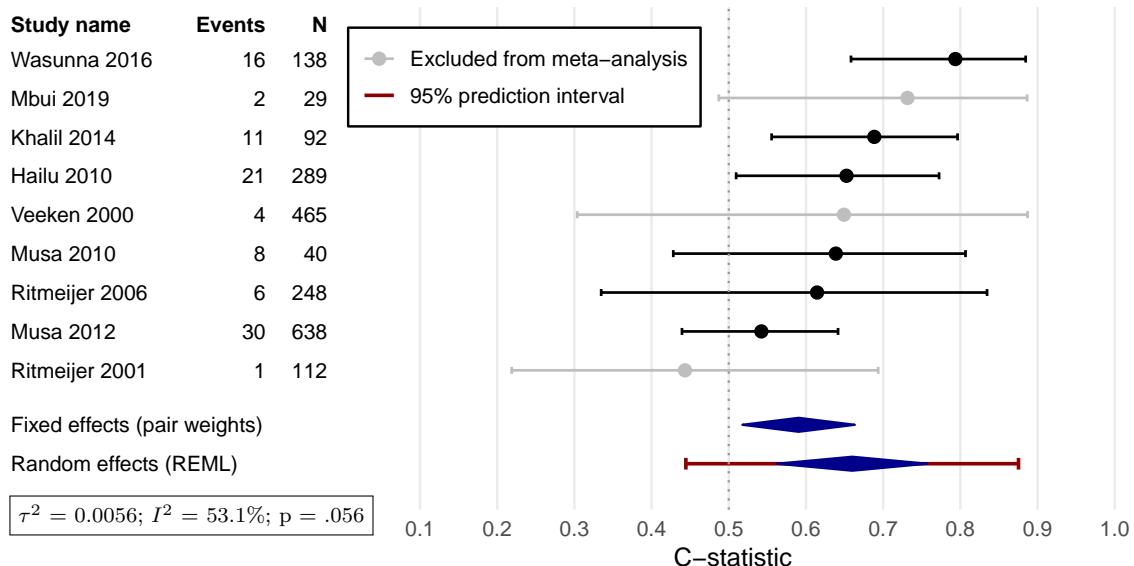


Figure D.27: Forest plot showing individual and pooled study c-statistics, for the model **excluding** parasite grade. Pooled c-statistics are presented from both fixed-effects and random-effects meta-analysis models. Pooled random-effects c-statistics and variances are estimated using restricted maximum likelihood (REML) and the Hartung–Knapp–Sidik–Jonkman method. Study-specific confidence intervals should be interpreted with caution due to small sample sizes and relapse events in some studies (see Methodology Section 4.3.7). Blue diamonds: pooled summary estimates with 95% confidence intervals. Red line: 95% prediction interval. Study ordered by c-statistic.

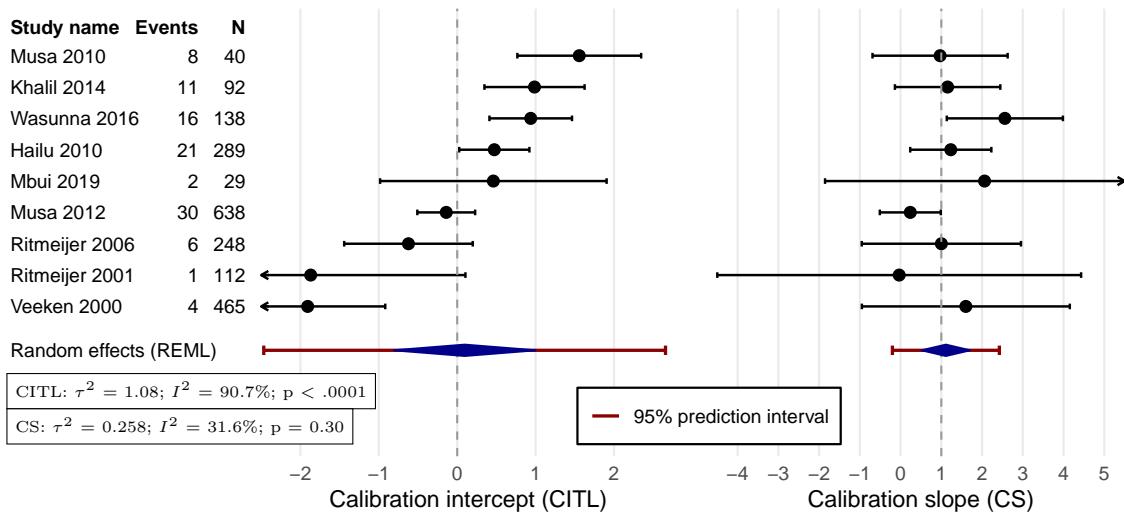


Figure D.28: Forest plots showing individual and pooled study calibration measures for the model **excluding** parasite grade. Left: calibration intercept (calibration-in-the-large, CITL); Right: calibration slope (CS). Blue diamonds: summary estimates with 95% confidence intervals.

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