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ORIGINAL ARTICLE

The incidence, mortality and timing of *Pneumocystis jiroveci* pneumonia after hematopoietic cell transplantation: a CIBMTR analysis

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Pneumocystis jiroveci pneumonia (PJP) is associated with high morbidity and mortality after hematopoietic stem cell transplantation (HSCT). Little is known about PJP infections after HSCT because of the rarity of disease given routine prophylaxis. We report the results of a Center for International Blood and Marrow Transplant Research study evaluating the incidence, timing, prophylaxis agents, risk factors and mortality of PJP after autologous (auto) and allogeneic (allo) HSCT. Between 1995 and 2005, 0.63% allo recipients and 0.28% auto recipients of first HSCT developed PJP. Cases occurred as early as 30 days to beyond a year after allo HSCT. A nested case cohort analysis with supplemental data ($n = 68$ allo cases, $n = 111$ allo controls) revealed that risk factors for PJP infection included lymphopenia and mismatch after HSCT. After allo or auto HSCT, overall survival was significantly poorer among cases vs controls ($P = 0.0004$). After controlling for significant variables, the proportional hazards model revealed that PJP cases were 6.87 times more likely to die vs matched controls ($P < 0.0001$). We conclude PJP infection is rare after HSCT but is associated with high mortality. Factors associated with GVHD and with poor immune reconstitution are among the risk factors for PJP and suggest that protracted prophylaxis for PJP in high-risk HSCT recipients may improve outcomes.

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INTRODUCTION

Pneumocystis jiroveci (formerly *Pneumocystis carinii*) pneumonia (PJP), a unicellular fungal infection, is a severe infectious complication in immunocompromised hosts, including hematopoietic stem cell transplant (HSCT) recipients, often leading to fulminant respiratory failure.[1–3] In immunocompromised hosts, PJP disease confers increased mortality, with published historical rates as high as 34–62%,[4–7] although data in the current era are unknown due to the rarity of disease with the implementation of routine PJP prophylaxis. Prior to prophylaxis, PJP disease was reported in 5–37% of HSCT patients.[8,9] However, since the advent of PJP prophylaxis, this incidence has decreased, with recent reports suggesting 1–6%[4,7,9–13] and a few reports of no cases in as many as 120 high-risk HSCT recipients.[14] However, with this rarity of disease, the actual incidence of PJP after HSCT remains unknown, as the largest number of PJP cases in reports is often under 10, suggesting that these data may overestimate the true incidence due to reporting bias, since cohort studies are often undertaken in the setting of outbreaks.[15–17]

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Multiple studies have suggested that trimethoprim/sulfamethoxazole (TMP/SMX) is the drug of choice to prevent PJP in immunocompromised patients due to its efficacy against PJP and concurrent prophylaxis against other opportunistic pathogens including *Toxoplasma gondii, Nocardia* and susceptible bacteria (e.g. *Staphylococcus*, *Streptococcus pneumoniae*).[1,5,8,10,18] However, it is not well tolerated in HSCT recipients, with reported intolerance as high as 55% requiring discontinuation of the drug due to rash, marrow suppression and allergy.[19–23] For these TMP/SMX-intolerant patients, PJP prophylaxis alternative agents include aerosolized or IV pentamidine, dapsone, atovaquone, clindamycin and pyrimethamine, though clindamycin and pyrimethamine have been largely abandoned due to lack of efficacy.[20,22–25] However, there is no consensus regarding efficacy of these agents in HSCT patients, nor an appropriate algorithm for choosing among these second-line agents. PJP breakthrough rates are as high as 9% for aerosolized pentamidine, 7.2% for dapsone, and not well categorized for IV pentamidine and atovaquone, with several anecdotal reports of failures with these agents, although these account for less than 300 total reported patients.[26–30] As a result of these sparse data, the most recent recommendation from the Cochrane Collaboration includes only TMP/SMX and suggests continuation for at least 6 months after HSCT and continuation until discontinuation of immune suppression.[10,31]

PJP disease risk and clearance rely upon recovery of lymphocyte numbers and function. Not surprisingly, published factors linked to PJP infection after HSCT are those associated with lymphocyte impairment, including steroids, T-cell depletion *in vitro* or *in vivo,* persistent lymphopenia, immunosuppression, GVHD and relapse.[4,11,32–35] The highest period of risk for PJP is thought to be from day 80 through day 270 post-HSCT due to impaired lymphocyte function during this time frame, though very early and very late cases have been described.[4,18,36–39] While these risk factors are likely determinants of PJP disease, there are conflicting reports, and small sample size limits interpretation.

Since PJP is an uncommon event in the HSCT population, the incidence, timing, risk factors and best prophylaxis regimens may only be addressed in a large registry study, which overcomes the limitation of disease rarity. The reported high mortality underscores the need for these data, to both determine the true mortality in a sufficiently large cohort and reveal the population most at risk, for whom new interventions could be targeted. Thus, we interrogated the largest HSCT database, the Center for International Blood and Marrow Transplant Research (CIBMTR) registry, to identify the incidence of PJP, and then performed a nested case control study to assess risk factors and PJP-associated mortality, and to provide evidence-based data for choice of prophylaxis agents for HSCT recipients.

PATIENTS AND METHODS

Data source

The CIBMTR is a voluntary working group of more than 450 transplantation centers worldwide that contribute detailed data on consecutive HSCTs to a Statistical Center located at the Medical College of Wisconsin in Milwaukee and the National Marrow Donor Program Coordinating Center in Minneapolis. Participating centers are required to report all transplantations consecutively; compliance is monitored by onsite audits. The CIMBTR maintains an extensive database of detailed patient-, transplant- and disease-related information, and prospectively collects data longitudinally with yearly follow-ups. Observational studies conducted by the CIBMTR are performed in compliance with Health Insurance Portability and Accountability Act of 1996 (HIPAA) regulations as a public health authority and also in compliance with all applicable federal regulations pertaining to the protection of human research participants, as determined by a continuous review by the Institutional Review Boards of National Marrow Donor Program and the Medical College of Wisconsin.

Patients

This study includes all patients, irrespective of age, who received HSCT for either malignant or non-malignant indications between 1995 and 2005 and identified with PJP infection within 2 years of transplantation. PJP infection was captured in the CIBMTR data forms either as an infection documented in the post-transplant period or listed as a primary or secondary cause of death. Centers report based upon organism identification and those cases reported as suspected fungal infection were excluded. Those with a history of PJP infection prior to HSCT were excluded. A subsequent analysis was performed to interrogate incidence only using the same inclusion and exclusion criteria from 2006 to 2012.

Analysis

This is a nested case control cohort study to assess clinical factors impacting the development of PJP and outcomes. Controls were selected 3:1 based on (1) type of transplant (autologous or allogeneic), (2) the same duration of post-HSCT follow-up (ensuring controls are alive at the time of case PJP diagnosis), and (3) the same disease indication for HSCT. A marginal proportional hazards model for clustered data was used for matching.[40] Supplemental data forms were requested to evaluate PJP prophylactic agents, concomitant neutrophil and lymphocyte counts, and methods of PJP diagnosis including autopsy, bronchoalveolar lavage and methenamine silver. β-D-Glucan was not included as a diagnostic modality due to the study period evaluated. We received supplemental data on 97 cases (57%) and 236 controls (47%). Data forms were missing PJP prophylaxis data for 14 cases (14%) and 21 controls (9%), and the time of administration of prophylaxis was reported as unknown for 28 cases (29%) and 45 controls (19%). Therefore, detailed prophylaxis medication within the 30 days prior to the diagnosis of PJP was only available for 33% of cases and 34% of controls (Figure 1). Consequently, information on PJP prophylaxis is described but could not be analyzed as a risk factor for PJP.

The effect of PJP infection on overall survival of the entire study population was assessed using a proportional hazards model adjusting for the effect of other significant covariates including time-dependent variables of PJP infection (main effect variable) and GVHD; GVHD was incorporated as a variable in the multivariable model, such that the GVHD event must have occurred prior to the PJP infection to be evaluable. This precludes studying GVHD as an outcome. Interactions between PJP infection and significant covariates were tested. Backward elimination was used to select significant covariates. Analysis was performed using SAS 9.2.

RESULTS

Incidence and timing of PJP infection after HSCT

Between 1995 and 2005, the incidence of PJP was 0.63% in allogeneic recipients ($n = 177$ cases of 27 934 total) and 0.28% in autologous recipients ($n = 52$ cases of 18 525 total). This has not changed with time as the incidence was 0.53% in allo recipients and 0.32% in auto recipients from 2006 to 2012. PJP developed both early (between days 0 and 60) and late (beyond day 270) after allo HSCT. PJP occurred at a median of 120 days (range, 2–620 days), with 26% of cases occurring early (median 31,

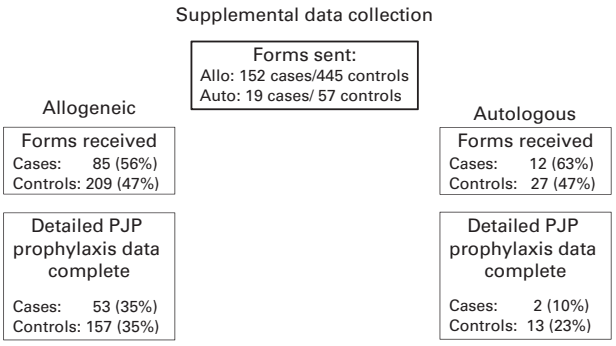

Figure 1. This chart summarizes the cases included in the supplemental data collection for allogeneic and autologous HSCT recipients.

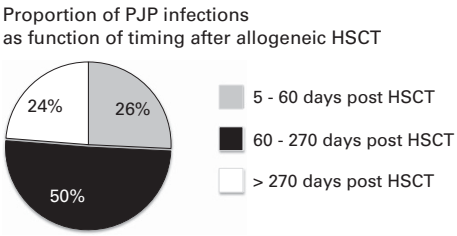

Figure 2. Timing of PJP after allogeneic HSCT. This chart shows the relationship between time after allogeneic HSCT and development of PJP disease.

range 5–56 days), 50% occurring between 60 and 270 days after HSCT (median 120, range 60–265 days) and 24% occurring late (median 342, range 279–587 days) (Figure 2). After auto HSCT, although the numbers were small, a similar trend was observed with 18% prior to day 60, 55% between day 60 and 270, and 27% after day 270. Of those that completed the secondary forms, bronchoalveolar lavage was the most common method of diagnosis for allogeneic and autologous recipients, for allogeneic recipients, this totaled 74%, though autopsy (2%), biopsy (4%), sputum (9%), imaging (9%) and methanamine silver (2%) were also reported.

Table 1. Risk factors associated with PJP disease after allo and auto HSCT

Variable	*Case* N *(%)*	*Controls* N *(%)*	P-*value*
Allogeneic HSCT			
Number of patients	152	445	
Gender, male	96 (63)	252 (57)	0.159
Age, median (range), years	33 (< 1–70)	30 (< 1–72)	0.361
Race			0.001
Caucasian	107 (70)	372 (84)	
African-American	6 (4)	9 (2)	
Asian	22 (14)	35 (8)	
Hispanic	14 (9)	14 (3)	
Native American	1 (< 1)	1 (< 1)	
Other	2 (1)	14 (3)	
Graft type			0.027
Bone marrow	90 (59)	311 (70)	
Peripheral blood	57 (38)	116 (26)	
Cord blood	5 (3)	18 (4)	
Sex match (donor/recipient)			0.115
Male–Male	50 (33)	160 (36)	
Male–Female	30 (20)	101 (23)	
Female–Male	44 (29)	90 (20)	
Female–Female	25 (16)	91 (20)	
Missing	3 (2)	3 (< 1)	
CMV match (donor/recipient)			0.201
Neg/Neg	37 (24)	139 (31)	
Pos/Neg	16 (11)	50 (11)	
Neg/Pos	35 (23)	82 (18)	
Pos/Pos	52 (34)	155 (33)	
Missing	12 (8)	19 (4)	
Conditioning intensity			0.414
Myeloablative	117 (77)	353 (79)	
Non-myeloablative/ reduced	30 (20)	85 (19)	
Missing	5 (3)	7 (2)	
Degree of HLA match			< 0.001
HLA-identical sibling	73 (48)	310 (70)	
Other related	10 (7)	12 (3)	
Well matched unrelated	28 (18)	51 (11)	
Partially matched unrelated	24 (16)	32 (7)	
Mismatched unrelated	14 (9)	29 (7)	
Missing	3 (2)	11 (2)	
Immunosuppressive agents within 30 days of PJP diagnosis[a]			< 0.001
None	10 (7)	44 (10)	
Yes, steroid containing	52 (34)	78 (18)	
Yes, non-steroid containing	21 (15)	84 (19)	
Missing	2 (1)	3 (< 1)	
GVHD prophylaxis			< 0.001
Ex vivo T-cell depletion alone	8 (5)	23 (5)	
Ex vivo T-cell depletion +post- HSCT immune suppression	5 (3)	37 (8)	
CD34 selection alone	2 (1)	0	
CD34 selection+post-HSCT immune suppression	5 (3)	5 (1)	
FK506+MMF ± others	3 (2)	4 (< 1)	
FK506+MTX ± others (− MMF)	27 (18)	11 (2)	
FK506+others (− MTX, MMF)	3 (2)	4 (< 1)	
CSA+MMF ± others (− FK506)	3 (2)	21 (5)	
CSA+MTX ± others (− FK506, MMF)	68 (45)	259 (58)	
CSA+others (− FK506, MTX, MMF)	22 (14)	67 (15)	
Other GVHD prophylaxis	6 (4)	14 (3)	
Antithymocyte globulin/ Alemtuzamab			0.022
Antithymocyte globulin only	43 (28)	102 (23)	
Alemtuzamab only	7 (5)	5 (1)	
Neither	102 (67)	337 (76)	
Missing	0	1 (< 1)	
Year of HSCT			< 0.001
1995–1996	39 (26)	139 (13)	
1997–1998	28 (18)	103 (23)	
1999–2000	26 (17)	54 (12)	
2001–2002	20 (13)	77 (17)	
2003–2004	29 (19)	71 (16)	
2005	10 (7)	1 (< 1)	
Autologous HSCT			
Number of patients	19	57	
Gender, male	10 (53)	28 (49)	0.791
Age, median (range), years	58 (4–71)	45 (2–68)	0.060
Race			0.601
Caucasian	18 (95)	50 (88)	
African-American	0	3 (5)	
Asian	0	1 (2)	
Hispanic	1 (5)	1 (2)	
Other	0	2 (4)	
Co-existing autoimmune disease			0.04
No	17 (89)	56 (98)	
Yes	2 (11)	0	
Missing	0	1 (2)	

[a]For those with supplemental information.

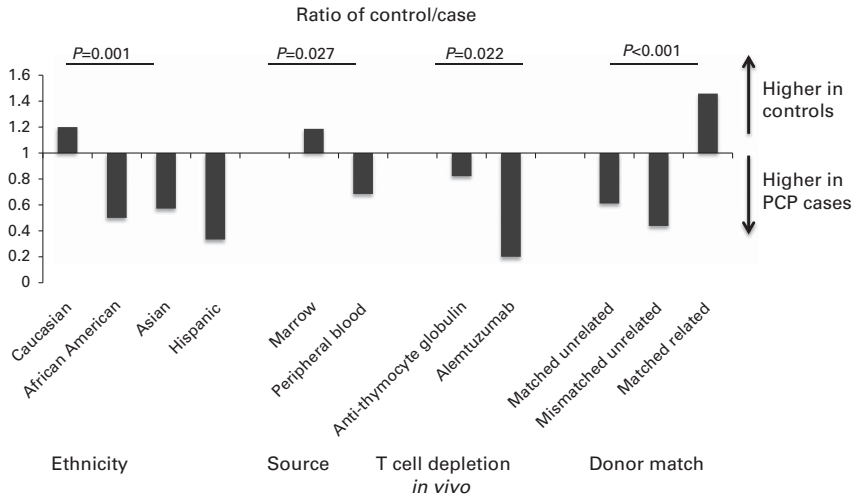

Figure 3. Relative risk (RR) of PJP control/case after allogeneic (allo) HSCT. The relative risk of controls to PJP cases for risk factors after allo HSCT shows that non-Caucasian ethnicity, peripheral blood stem cell source, T-cell depletion (TCD) *in vivo* and donor mismatch were high in PJP cases vs controls were significantly associated with PJP infection compared with controls after allo HSCT.

Risk factors for PJP infection after HSCT

Cases and controls were similar in terms of gender, age, Karnofsky score, coexisting endocrine or pulmonary diseases, disease status at the time of transplant, and prior autologous HSCT for both autologous and allogeneic recipients (Table 1). For allogeneic recipients, sex mismatch, intensity of conditioning regimen and CMV mismatch were not significantly different between cases and controls by univariate analysis. After auto HSCT, coexisting autoimmune disease ($P < 0.05$) and lymphopenia ($P < 0.04$) were more likely in cases as compared with controls. Lymphocyte number for the cases was 622 (range 0–1260) vs 1170 in controls (range 0–4758). While recent steroid use was more prevalent in cases than in controls after auto HSCT (16% vs 2% respectively), this did not achieve statistical significance. After allo HSCT, lymphopenia ($P < 0.001$) and use of immunosuppressive agents ($P < 0.001$) were significantly greater in PJP cases vs controls. Lymphocyte numbers were 400 in cases (range 0–7000) vs 810 (range 0–6270) in controls. Relapse was also evaluated as a risk factor after allo HSCT; however, only 14% of patients with malignant indications for HSCT developed PJP after relapse suggesting that this was not a significant factor for the development of PJP disease. Collectively, these data suggest that PJP disease is most likely associated with impaired lymphocyte reconstitution after auto or allo HSCT. In addition, non-Caucasian ($P = 0.001$), peripheral blood stem cell source ($P = 0.027$), administration of GVHD prophylaxis other than tacrolimus/methotrexate ($P < 0.001$) and/or alemtuzumab/ATG ($P = 0.022$), more recent year of transplant ($P < 0.001$) and greater HLA mismatch ($P < 0.001$) were significantly associated with PJP infection compared with controls after allo HSCT (Figure 3).

Association of GVHD with PJP infection after HSCT

For allogeneic recipients, acute and chronic GVHD was higher in PJP cases than controls. Of PJP cases, 27% had grade 3–4 acute GVHD compared with 14% of controls, with 73% of controls experiencing none or grade 1 GVHD vs 57% of cases (Figure 4). Fifty-five percent of cases lacked chronic GVHD vs 61% of controls. However, for patients developing PJP beyond day 270, 79% of cases experienced cGVHD vs 44% of controls. While the transplant time period precluded analysis of severity of chronic GVHD, 33% of cases who developed PJP greater than 270 days after HSCT had been exposed to steroids prior to development of PJP, compared with 0% of controls, which could be a reflection of more significant GVHD.

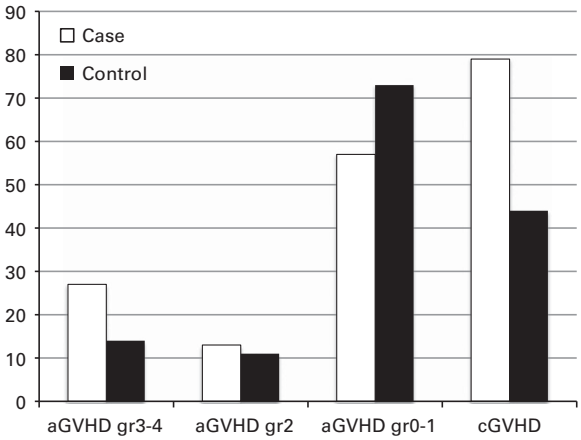

Figure 4. Acute and chronic GVHD in PJP cases vs controls. Prevalence of acute and chronic GVHD after allo HSCT in PJP cases was higher than in controls.

Association of PJP prophylaxes and risk of PJP infection

Determination of the breakthrough risk of PJP as a function of PJP prophylaxis agents was limited due to both missing and incomplete secondary forms. This large quantity of missing or incomplete data precluded statistical analyses of the association between PJP prophylaxis regimens and the risk of PJP infection. For description, 'time unknown' is combined with the known prophylaxis. Despite these limitations, more cases received only inhaled pentamidine for both autologous (10% of cases vs 2% of controls) and allogeneic (20% of cases vs 2% of controls) recipients developing PJP (Figures 5a and b). Additionally, in allogeneic recipients there was a case of IV pentamidine alone and none in controls (Table 2). Allogeneic cases were more likely to be on prophylaxis greater than 60 days after HSCT—likely due to recognition of impaired immune reconstitution, though less likely to receive TMP/SMX prophylaxis. Overall, 14% of cases and 15% of controls were on no prophylaxis in the 30 days prior to the onset of PJP infection.

Mortality after PJP infection

After allo HSCT, overall survival was significantly poorer among PJP cases vs controls (1 year: 41% vs 73% ($P < 0.0001$); 5 year: 25%

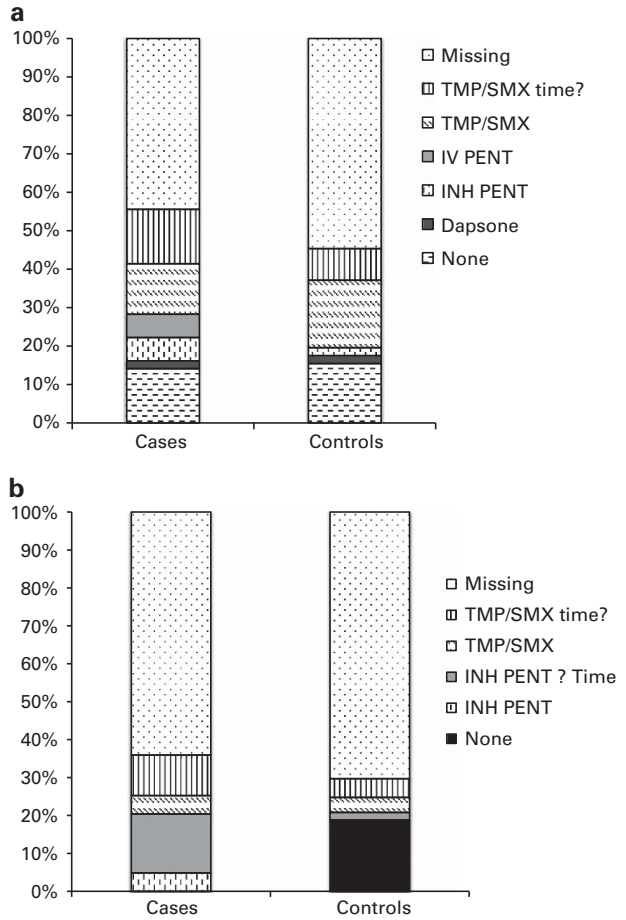

Figure 5. PJP prophylaxis agent association with breakthrough risk after allo HSCT (**a**) and auto HSCT (**b**). Using secondary forms, the use of PJP prophylaxis agents was interrogated in PJP cases and controls after allo HSCT (**a**) and auto HSCT (**b**). Notably, missing data was included as a variable (TMP/SMX of time? = trimethoprim/sulfamethoxazole of uncertain timing in relation to PJP disease or control time point, IV PENT = intravenous pentamidine, INH = inhaled), none = the center confirmed the absence of PJP prophylaxis).

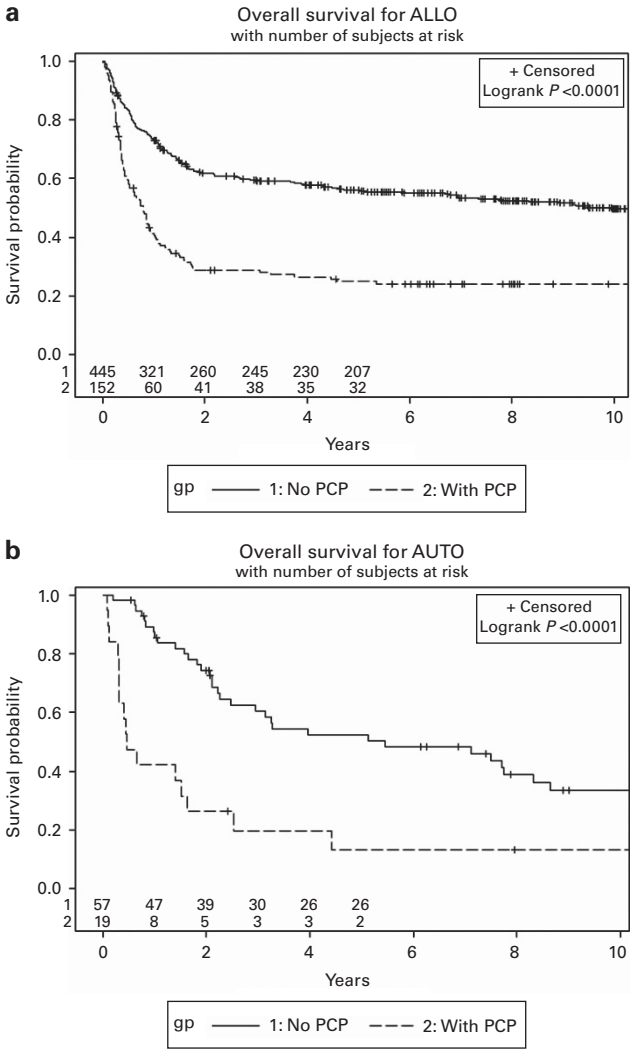

Figure 6. Kaplan Meier survival for PJP cases and controls after allo (**a**) and auto (**b**) HSCT.

vs 56% ($P < 0.0001$)) (Figure 6a). Similarly, following auto HSCT, overall survival was lower in cases vs controls (1 year: 42% vs 86% ($P = 0.0004$); 5 year: 13% vs 52% ($P = 0.0003$)) (Figure 6b). Mortality was directly attributable to PJP in nearly a quarter of HSCT recipients (auto, 24%; allo, 23%). For allo HSCT cases, other infections were the largest second contributor to mortality (21%). In auto HSCT cases, recurrent disease accounted for 43% of deaths in PJP cases and 69% of controls. After controlling for significant variables (age, mismatch, race, GVHD prophylaxis, year of HSCT, aGVHD), PJP cases had a 6.87-fold increase in mortality ($P < 0.0001$, 95% CI 4.84–9.75, $P < 0.0001$).

DISCUSSION

We have evaluated the incidence, risk factors, timing and mortality for PJP in HSCT recipients using a large HSCT registry. The CIBMTR database included over 50 000 allogeneic recipients at the time of the data query, overcoming common limitations of prior studies, including those of small patient numbers and single institution data. We show that the incidence of PJP following allogeneic and autologous HSCT is much less common than prior publications have suggested. This lower rate is likely due to freedom from publication bias; centers were more likely to publish their findings after an outbreak of PJP, enriching for this rare disease. This suggestion is supported by the fact that large multi-year studies including all infections affecting HSCT recipients often report lower rates of PJP infections as compared with smaller PJP-focused studies (1% vs 2.5–6%).[4,7,9–13] This is further supported by the fact that although PJP infections were initially thought to represent an opportunistic event related to chronic colonization, genotyping of *P. jiroveci* in clusters has confirmed that *de novo* outbreaks do occur in immunosuppressed patients, and could prompt these publications.[1,15–17,41] Interestingly, despite the increased sensitivity of disease detection including the use of β-D-glucan testing,[42–48] and improving survival of severely immunosuppressed patients, the incidence of PJP after HSCT has not increased over time, consistent with the hypothesis that prophylaxes are protective in HSCT patients.[8,20,26,49–53] Notably, our data are unable to assess for a true incidence of PJP in patients on any prophylaxis (i.e. breakthrough PJP) due to the nested case cohort study design. However, since similar numbers of cases and controls (14–15%) within the subset of patients with supplemental data were not on prophylaxis, our estimated overall incidence of PJP following allogeneic and autologous HSCT are a reasonable estimate of the true incidence of PJP after HSCT.

Table 2. Known PJP prophylaxis therapies and development of PJP as a function of time after allo HSCT

	Time after HSCT					
	< 60 days		*60–270 days*		*>270 days*	
Proportion of PJP cases	26%		51%		24%	
	Cases	Controls	Cases	Controls	Cases	Controls
Bactrim prophylaxis use	36%	35%	14%	43%	11%	21%
No prophylaxis	7%	35%	34%	20%	26%	50%
Dapsone	0%	0%	0%	0%	0%	1%
Pentamidine as part of regimen	14%	8%	17%	4%	0%	0%
Missing data	21%	13%	11%	6%	5%	9%

Above is a table showing the proportion of cases and controls who received these known prophylaxis regimens in relation to the timing of the case onset of PJP. Notably, the pentamidine data could include inhaled or IV medication. Time unknown data were excluded from this table (though included in Figures 4a and b) and missing data show the forms returned without this prophylaxis section completed.

Our data show that PJP infection occurred both early and late after HSCT. Prior reports have often highlighted the period between day 80 and 270 after HSCT as the time of highest risk, with some including up to 1 year.[18,36] In contrast, our data reveal 26% of cases occur before day 60, with the earliest event just 5 days after HSCT.[18,36] Current practice often involves PJP prophylaxis before or during the preparative regimen, to 'diminish PJP burden', and re-institution of prophylaxis after counts have recovered due to medication intolerance (e.g. blood count suppression with TMP/SMX, intolerance for inhaled pentamidine) or challenges with oral absorption (atovaquone).[31,54] In addition, while 50% of cases did occur in the period that has been most reported most often previously as the period of highest risk (days 80–270), 24% occurred after day 270, with a median of nearly a year, suggesting that the recommendation of a year of prophylaxis may be insufficient. These data suggest that PJP prophylaxis should be started early and continued late (beyond a year)—at least for patients at highest risk for this disease, with the caveat that these suggestions are limited by the retrospective nature of this study.

This study identifies risk factors for PJP disease, including some of those reported in prior studies such as corticosteroid exposure, *in vivo* or *in vitro* T-cell depletion, lymphopenia, immunosuppression and GVHD.[4,11,32–35,39,55] After auto HSCT, factors associated with ongoing immunosuppression, such as coexisting autoimmune disease and lymphopenia, were higher in PJP patients, although a previously identified risk factor steroids did not achieve statistical significance as a risk factor for PJP disease. This likely reflects the small sample size, as steroids were more common in the PJP diseased cohort. After allo HSCT, factors associated with impaired immune reconstitution (steroid exposure, lymphopenia, neutropenia) and/or GVHD, non-Caucasian decent, peripheral blood stem cell graft, receipt of either GVHD prophylaxis other than tacrolimus/methotrexate and/or alemtuzumab/ATG, and greater HLA mismatch were more common in PJP patients as compared with controls. This is not surprising as PJP eradication relies upon functional CD4 immunity, which is impaired in the setting of GVHD and steroid exposure. As anticipated from these data, lymphopenia as well as both acute and chronic GVHD were greater in recipients developing PJP. Both the aberrant lymphocyte response to infection in patients with GVHD and the effect of immune suppressive therapy likely contribute to the heightened risk for opportunistic infections. In addition, impaired immune reconstitution can occur in the absence of these overt risk factors, due to absence of thymus reconstitution and/or the use of HLA-mismatched grafts, which may demonstrate absent CD4+ cell function with or without normal peripheral counts.[56] Together, these data suggest that those HSCT patients with impaired immunity (from GVHD, steroids, T-cell antibody therapy or other factors predictive of T-cell dysfunction) should start PJP prophylaxis early and continue on such prophylaxis until functional immunity is restored—evidenced both by CD4+ cell reconstitution and functional immunity via vaccine response or evidence of thymus reconstitution.

While missing data preclude full analysis of the relative efficacy of PJP prophylaxis agents, our data do provide some possible insights into this important question. Most surprisingly, approximately 15% of cases and controls were on no agent for PJP prophylaxis following allogeneic HSCT. This could suggest either patients did not adhere to the recommended regimen or because physician practice did not include PJP prophylaxis, which would be particularly important in high-risk patients at high-risk time frames after HSCT. Not surprisingly, after auto HSCT, more controls were on no prophylaxis, likely reflecting remission, and/or absence of immune suppression. In both auto and allo patients, there were more cases with PJP vs controls receiving pentamidine, which has been previously suggested in one of the largest investigations of PJP disease in allo HSCT recipients.[23] Data from non-HSCT diseases have shown higher breakthrough rates for pentamidine as well, leading to recommendations of greater than the third-line choice for pentamidine for PJP prophylaxis.[31,34] Although one single center study suggests that IV pentamidine may provide efficacy, this was published during an outbreak of cases (with cases occurring despite known adherence to the pentamidine regimen), with unclear generalizability or efficacy in light of the rarity we report here. Further, data show that the IV route does not result in high intra-alveolar concentrations of drug, providing poor protection for high-risk patients.[57,58] In our study, there were similar cases and controls on dapsone (though small numbers), which may reflect the high rate of intolerance of this agent (greater than 40%) and concern regarding toxicities such as aplastic anemia and agranulocytosis, precluding interpretation of efficacy.[21,22,27,59] There were no cases or controls on atovaquone, though this may simply reflect the era of evaluation, given that atovaquone has only recently been incorporated in recommendations and requires fatty foods and oral absorption, limiting its use in HSCT patients.[31] Breakthroughs were also observed with the best prophylaxis agent, TMP/SMX, which may reflect decreased adherence, frequency of dosing or resistance of the organism, which is difficult to prove and often unknown.[60,61] Emerging, albeit anecdotal data have recently reported the activity of caspofungin against PJP,[62] though after the time frame of the current analysis. In summary, while these data are limited due to missing or incomplete secondary forms, our data would support that of prior publications that TMP/SMX be strongly recommended and careful consideration regarding cessation as no other alternative agent has been shown to be equally effective. Before stopping this medication for count suppression or rashes, perhaps, we recommend that TMP/SMX prophylaxis should be reconsidered in high-risk patients with growth factor support or desensitization utilized whenever possible, as has been

recommended by the recent international guidelines for PJP prophylaxis.[19,31]

Mortality was high in patients with PJP disease, with nearly seven-fold increased risk of death compared with matched controls. The absolute overall survival matches that previously published for early time points, approximately 40% at 2 years[4,5] and decreased with time to $<25\%$ at 5 years after allogeneic HSCT, and even lower for autologous recipients at 5 years. While this is compelling data that PJP portends poor survival, it is possible that PJP is a surrogate marker for other high-risk predictors of mortality due to impaired immunity or relapse as well.

There were several notable limitations to our study. The analyses addressing mortality, timing and associated risk factors including therapeutic prevention were limited by missing data due to secondary forms that were incomplete or not returned. Furthermore, limitations to our data include those of all registry studies, where data rely upon accurate capture of events into the database and that only a small proportion is audited for accuracy, thus possibly resulting in underestimation of the true incidence especially as time from HSCT increases and visits to the primary HSCT center decline. This could lead to intentional or accidental under-reporting, either from a desire to report positive results or due to missed data that was not captured, though one would postulate that both the anonymity of these data and the onus to responsibly report would drive accurate reporting and minimize this risk. Because the transplant center is more likely to be contacted for sick patients than for healthy controls, there may be increasing selection bias with longer time from transplantation as well.

In summary, our data demonstrate that the incidence of PJP disease is very low in autologous and allogeneic HSCT recipients, and most common among recipients with poor immune reconstitution, including those with mismatched grafts and GVHD. Our data demonstrate that PJP infection may occur at any time after HSCT and confers a high risk of mortality. In addition, these data suggest that TMP/SMX remains the most effective prophylactic drug. We provide guidance about duration of prophylaxis during periods of immune compromise, including very early and very late after HSCT.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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