

Temporal dynamics of PrEP adherence, self-efficacy, and risk perception among men who have sex with men in western China: A cross-lagged panel network analysis

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Abstract

Background

Pre-exposure prophylaxis (PrEP) effectively reduces HIV infection risk among men who have sex with men (MSM), but its benefit depends on adherence. The longitudinal item-level relationships among PrEP adherence, self-efficacy, and risk perception remain unclear.

Methods

This repeated-measures longitudinal study included 186 MSM in western China who completed three follow-up assessments from November 2019 to June 2023. PrEP adherence, self-efficacy, and risk perception were assessed at each wave. Cross-sectional network analysis and cross-lagged panel network analysis were used to examine contemporaneous and longitudinal associations. Network accuracy, stability, and robustness were evaluated using bootstrap and sensitivity analyses.

Results

Across all waves, the item “I can remember to take my medicine on time” was consistently the node most strongly associated with PrEP adherence. The item “When your sexual partner is upset about your use of it” showed high importance in cross-sectional networks. Longitudinal networks indicated strong autoregressive effects of PrEP adherence and stage-specific cross-lagged effects. From T1 to T2, adherence predicted partner-related self-efficacy, side-effect-related self-efficacy, and perceived side effects. From T2 to T3, adherence predicted habit-related experience and concerns about medication effectiveness.

Conclusions

PrEP adherence among MSM in western China is embedded in a dynamic system involving self-efficacy and risk perception. Stage-specific interventions targeting key psychological and behavioral factors may help improve PrEP adherence.

Introduction

Human immunodeficiency virus (HIV) infection remains a major global public health challenge. Men who have sex with men (MSM) bear a disproportionately higher burden of HIV compared with the general population, largely due to elevated exposure risk and complex sexual networks[1, 2]. In China, the prevalence of HIV among MSM remains high, with a national estimate of approximately 5.7%, and a particularly heavy burden observed in the southwestern regions[3, 4]. Pre-exposure prophylaxis (PrEP) has been proven to effectively reduce the risk of HIV infection among MSM[5, 6], but its real-world

uptake, persistence, and adherence remain suboptimal among MSM in China[7]. Given that the effectiveness of PrEP is highly dependent on adherence[8, 9], identifying key determinants of adherence is essential for optimizing PrEP implementation and enhancing HIV prevention outcomes[10].

Self-efficacy, a core construct in Bandura's social cognitive theory, refers to an individual's confidence in initiating a health behavior and maintaining it under challenging circumstances[11, 12]. Evidence from HIV-related studies indicates that self-efficacy is an important psychological foundation of medication adherence and is closely associated with adherence to antiretroviral therapy (ART) and related health outcomes[13, 14]. In PrEP research, self-efficacy has likewise been recognized as a key factor influencing initiation, persistence, and proper use of PrEP. Higher adherence self-efficacy is associated with greater willingness to use PrEP, stronger confidence in maintaining medication use, and better subsequent adherence[15, 16]. However, most existing studies conceptualize self-efficacy as a global construct, with limited attention to its heterogeneity across specific situations. Among MSM, PrEP use is embedded within daily routines, interpersonal interactions, and diverse risk contexts. Therefore, the specific dimensions of self-efficacy most closely linked to adherence in dynamic medication-taking processes remain to be further elucidated.

Risk perception refers to individuals' subjective assessment of a health threat and its consequences. In HIV prevention, it is a multidimensional construct encompassing both perceived risk of infection and concerns related to preventive behaviors[17]. Higher PrEP-related risk perception is generally associated with lower adherence, and different trajectories of risk perception exert heterogeneous effects on adherence[18]. Factors such as side effects, effectiveness, stigma, and medical mistrust have all been proven to influence PrEP uptake and adherence among MSM[7, 19, 20]. Existing evidence indicates that the association between risk perception and adherence is not simply linear[21]. Heightened risk perception may motivate greater emphasis on prevention, but concerns about social exposure or healthcare environment may reduce willingness to sustain PrEP. Moreover, risk perception evolves over time with medication experience, social interactions, and engagement with healthcare services[22], suggesting that its association with adherence may vary across stages and contexts. Accordingly, a multidimensional and dynamic perspective is warranted to further elucidate the associations between different components of risk perception and PrEP adherence among MSM.

While previous studies have provided important insights into PrEP-related behaviors among MSM, two major limitations remain. First, most studies have been cross-sectional and have primarily focused on factors associated with PrEP awareness, intention to use, uptake, or adherence at a single time point[23–26], limiting understanding of how these factors are dynamically related over time. Although some prospective studies have explored longitudinal trajectories of PrEP-related risk perception and adherence[18], they have largely focused on overall trends or latent trajectory classes[27], with limited attention to more fine-grained temporal associations among psychological and behavioral factors. Second, most studies have relied on traditional regression models or total-score analyses, treating constructs such as self-efficacy and risk perception as unitary variables[15, 24, 28]. This approach makes it difficult to identify direct links among specific components and to clarify their directional

relationships. Therefore, further research is needed to examine how PrEP adherence, self-efficacy, and risk perception interact at a more specific level among MSM, whether these associations change over time, and how distinct psychological and behavioral factors relate to adherence. Such evidence may help identify key risk and protective factors and inform more targeted interventions. To this end, an analytical approach capable of simultaneously characterizing direct associations among variables and their longitudinal dynamics is required.

Network analysis conceptualizes variables as interconnected nodes, with edges representing independent associations between variables after controlling for all other nodes[29]. Compared with traditional total-score approaches, network analysis can identify direct relationships among nodes and detect central nodes, thereby providing a more fine-grained basis for identifying potential intervention targets[30, 31]. This approach has been widely applied to complex psychological and behavioral problems such as depression and anxiety[32–34]. Cross-lagged panel network (CLPN) analysis further extends network analysis to longitudinal data by simultaneously estimating autoregressive and cross-lagged effects, allowing the examination of directional predictive relationships among nodes[35]. In recent years, CLPN has been used in longitudinal research on anxiety, cognitive functioning, and internet addiction[36–38], demonstrating its unique value for studying complex psychological and behavioral systems. However, in the field of PrEP adherence, self-efficacy, and risk perception, existing studies have still focused mainly on overall levels or associations between single factors, with limited attention to their longitudinal dynamic relationships at the item level.

Accordingly, based on a repeated-measures longitudinal study conducted among MSM in western China, this study integrated cross-sectional network analysis and CLPN analysis to systematically examine the dynamic interrelationships among PrEP adherence, self-efficacy, and risk perception. Specifically, we aimed to (1) investigate the structural relationships between PrEP adherence and related psychological and behavioral factors, as well as identify key nodes, at different cross-sectional time points, and (2) examine the longitudinal directional associations between PrEP adherence and specific components of self-efficacy and risk perception, thereby elucidating their dynamic pathways. The findings of this study may provide valuable insights into the development and maintenance of PrEP adherence, as well as the interplay among related psychological and behavioral factors, and may help identify key targets for precision interventions and optimize PrEP intervention strategies for MSM.

Method

Participants and procedures

This repeated-measures longitudinal study was conducted from November 2019 to June 2023 in western China (Chongqing, Sichuan, and Xinjiang). Eligible MSM were recruited through non-probability sampling via local nongovernmental organizations and peer referral. All participants provided written informed consent before enrollment. The study was approved by the Ethics Committee of Chongqing Medical University (Reference No. 2019001). The main inclusion criteria included: (1) biologically male at

birth; (2) 18–65 years old; (3) having had sexual intercourse with men in the past 6 months; (4) testing negative for HIV antigen and antibody; (5) willingness to take pre-exposure prophylaxis (PrEP) under study guidance and follow-up arrangements; (6) completion of all three follow-up assessments; (7) signed informed consent.

Eligible study participants were enrolled into the PrEP cohort and received a daily oral PrEP regimen. Follow-up visits were conducted every 12 weeks, during which participants completed questionnaire surveys and received medication for the next phase. All questionnaires were collected and managed by uniformly trained interviewers.

Measures

PrEP adherence rate

PrEP adherence was assessed at T1, T2, and T3 using self-report. Participants were asked whether they had missed any doses during the past 2 weeks and, if so, how many doses were missed. Adherence was calculated as: $100\% - (\text{number of missed doses} / \text{number of prescribed doses}) \times 100\%$.

The PrEP self-efficacy scale

PrEP self-efficacy refers to an individual's confidence in maintaining regular PrEP use across different situations and has been used in adherence research related to HIV treatment and prevention[13]. The HIV Adherence Self-Efficacy Scale (HIV-ASES), developed by Johnson et al.[39], was originally designed to assess confidence in adhering to ART under a range of challenging circumstances and has demonstrated good reliability and validity. In this study, the PrEP Self-efficacy Scale was adapted from the HIV-ASES framework to assess confidence in maintaining regular PrEP use across different life and psychological contexts among MSM. The scale consisted of eight items covering common situations that may affect PrEP adherence. Each item was rated on a 5-point Likert scale from 1 ("not at all confident") to 5 ("very confident"). The scale was administered at T1, T2, and T3. Cronbach's α coefficients were 0.92, 0.91, and 0.89 at T1, T2, and T3, respectively, indicating good internal consistency.

The PrEP risk perception scale

PrEP risk perception refers to the potential negative feelings, concerns, or mistrust experienced during PrEP use. In this study, risk perception was assessed using the PrEP Risk Perception Scale developed by Lin et al.[18], comprising four dimensions: personal experience, potential concerns, medication impacts, and medical mistrust. Personal experience reflects relief from fear of HIV infection and subjective feelings about regular medication use; potential concerns refer to worries about possible risks or problems related to PrEP use; medication impacts denote drug-related negative experiences; and medical mistrust pertains to distrust toward physicians or the healthcare environment during PrEP use. All items were rated on a 5-point Likert scale from 1 ("never") to 5 ("always"). Previous research has

demonstrated good structural validity of this scale[18]. The scale was administered at T1, T2, and T3, with Cronbach's α coefficients of 0.84, 0.84, and 0.86, respectively, indicating good internal consistency.

Network analysis

Cross-sectional network analysis

Cross-sectional network structures were estimated at T1, T2, and T3. Gaussian graphical models (GGMs) were constructed using the graphical least absolute shrinkage and selection operator (LASSO) with the extended Bayesian information criterion (EBIC) to identify conditional correlations among variables. Because the data may deviate from normality, variables were rank-transformed before analysis. In the cross-sectional networks, nodes represented study variables and edges represented conditional correlations between two nodes after controlling for all other variables in the network; edge thickness indicated the strength of the association, with blue edges indicating positive correlations and red edges indicating negative correlations. Expected influence (EI) was used to assess the relative importance of each node. EI identifies key nodes by summing the weights of all edges connected to a given node while retaining their signs[30].

Cross-lagged panel network analysis

CLPN analysis was conducted to examine the dynamic interrelationships among PrEP adherence, self-efficacy, and risk perception across time. CLPN simultaneously estimates (1) autoregressive effects, representing the predictive effect of the same variable over time, and (2) cross-lagged effects, representing the predictive effect of one variable on another over time. During model estimation, each path was adjusted for the effects of all other variables at the same time point to improve the independence and robustness of the estimates. Out-expected influence (out-EI) and in-expected influence (in-EI) were calculated to assess the role of each node in the longitudinal network. Out-EI reflects the overall predictive influence of a node on other subsequent nodes, whereas in-EI reflects the extent to which a node is influenced by other nodes at the previous time point[31].

Network accuracy and stability analysis

The accuracy of edge-weight estimates and the stability of centrality indices were evaluated. First, nonparametric bootstrap was used to estimate 95% confidence intervals (CIs) for edge weights, with narrower CIs indicating greater accuracy. Second, case-dropping bootstrap was used to calculate the correlation stability coefficient (CS-C) to assess the stability of centrality indices under subsampling. In addition, edge-weight difference tests and centrality difference tests were performed to examine whether the importance of different edges or nodes differed significantly.

All analyses were conducted in R (version 4.3.3), including descriptive statistics, cross-sectional network analysis, cross-lagged panel network analysis, and assessments of accuracy and stability. Missing data were handled using multiple imputation with the mice package[40]. Cross-sectional networks were

estimated as Gaussian graphical models using the estimateNetwork function in the bootnet package[29]. CLPN analysis was performed using the glmnet package within a regularized regression framework, with cross-validation used to reduce overfitting[41, 42]. Network visualization was performed using the qgraph package[43], and network accuracy and stability were assessed using the bootnet package[29].

Sensitivity analysis

To assess the robustness of the primary findings, we performed sensitivity analysis. This analysis included only participants who completed both the T1 and T2 follow-up assessments, and the cross-sectional networks at T1 and T2 as well as the T1-to-T2 cross-lagged panel network were re-estimated in this subsample. The data processing procedures, network estimation methods, parameter settings, and assessments of accuracy and stability were identical to those used in the main analysis.

Results

Participant characteristics and descriptive statistics

The primary analysis used a complete-case approach, including only participants who completed all three survey waves (T1, T2, and T3). The sociodemographic information is shown in **Table S1** in the supplementary material. Table 1 summarizes the 25 variables included in the network analysis, along with their item descriptions, node labels, and means (SD). These variables comprised (1) PrEP adherence (adherence rate, AR); (2) eight items from the PrEP self-efficacy scale (SE1–SE8); and (3) 16 items from the PrEP risk perception scale, covering four dimensions: personal experience (PE1–PE4), medication impacts (MI1–MI3), potential concerns (PC1–PC7), and medical mistrust (MM1–MM2).

Table 1
Item labels and descriptive statistics at T1, T2, and T3 (N = 186).

Instrument and items	Label	T1	T2	T3
N = 186		Mean(SD)	Mean(SD)	Mean(SD)
Medication adherence rate in the past two weeks	AR	0.77(0.38)	0.72(0.38)	0.74(0.37)
PrEP adherence self-efficacy scale				
When HIV prevention medication is not immediately available	SE1	2.76(1.22)	2.70(1.21)	2.86(1.24)
When you are (recently) drinking alcohol or using other drugs	SE2	2.68(1.12)	2.59(1.14)	3.01(1.21)
When your sexual partner is upset about your use of it	SE3	3.08(1.19)	2.95(1.21)	3.28(1.18)
When you experience side effects from it	SE4	2.58(1.09)	2.61(1.12)	3.02(1.17)
When using HIV prevention medication becomes too much of a hassle	SE5	2.82(1.11)	2.78(1.18)	3.11(1.17)
When you think your sexual partner will get angry about your use of HIV prevention medication	SE6	3.03(1.21)	3.01(1.26)	3.26(1.23)
When you believe your risk of contracting AIDS is very low	SE7	3.15(1.24)	3.18(1.28)	3.35(1.27)
When you are already using other protective measures (e.g., condoms)	SE8	3.38(1.21)	3.45(1.22)	3.70(1.18)
PrEP risk perception scale				
Personal experience and self-efficacy				
I think medicine make me safe, away from AIDS	PE1	3.67(1.24)	3.78(1.21)	3.87(1.18)
I can remember to take my medicine on time	PE2	3.55(1.16)	3.66(1.21)	3.80(1.14)
My fear of AIDS is lessened	PE3	3.28(1.24)	3.46(1.16)	3.50(1.16)
I'm used to taking medicine	PE4	2.87(1.30)	3.11(1.34)	3.19(1.34)
Medicine impacts				
I find it difficult to swallow medicine	MI1	1.83(0.98)	1.99(1.12)	1.97(1.14)
The smell of medicine makes me feel uncomfortable	MI2	1.72(0.92)	1.84(1.01)	1.85(1.09)

Instrument and items	Label	T1	T2	T3
The dosage form of medicine I do not like to take potential concerns	MI3	1.70(0.96)	1.78(1.04)	1.80(1.05)
I worry that the medicine has no effect	PC1	2.05(0.94)	2.05(1.04)	2.10(1.06)
I worry about the side effects of medicine	PC2	2.55(1.10)	2.37(1.10)	2.28(1.05)
I'm worried that homosexual partners know I'm taking medicine	PC3	2.00(1.04)	1.93(1.08)	2.04(1.15)
I worry that other people will discriminate me when they know I am on medicine	PC4	2.30(1.12)	2.26(1.20)	2.33(1.24)
I felt the side effects of the medicine	PC5	1.83(0.96)	1.95(1.11)	1.83(0.99)
I find it inconvenient to take the medicine	PC6	1.78(0.96)	1.74(1.01)	1.69(0.95)
I think it's very troublesome to take the medicine	PC7	1.82(0.93)	1.96(1.07)	1.84(0.99)
Medical mistrust				
I think the doctors here discriminate against me	MM1	1.37(0.88)	1.31(0.89)	1.36(0.96)
I trust the doctors here	MM2	4.15(1.29)	4.36(1.21)	4.50(1.11)

Cross-sectional network structures

Figure 1 presents the cross-sectional network structures and node centrality indices at T1, T2, and T3. The corresponding weighted adjacency matrices are provided in **Tables S2-S4**.

Across all three time points, AR (“adherence rate”) was conditionally associated with multiple psychological and behavioral variables, with its strongest positive association consistently observed with PE2 (“I can remember to take my medicine on time”) (Fig. 1.A–C). Although the overall network structure varied somewhat across time, several edges showed stable patterns. Specifically, SE7 (“When you believe your risk of contracting AIDS is very low”) and SE8 (“When you are already using other protective measures”), as well as PC3 (“I’m worried that homosexual partners know I’m taking medicine”) and PC4 (“I worry that other people will discriminate me when they know I am on medicine”), showed strong positive associations across all three waves. In contrast, MM1 (“I think the doctors here discriminate against me”) and MM2 (“I trust the doctors here”) showed a stable strong negative association across time.

Regarding node centrality, the most influential nodes varied slightly across time. However, SE3 (“When your sexual partner is upset about your use of it”) had the highest expected influence at T1 and T3 and ranked second at T2 (Fig. 1.D–F), indicating that it remained highly important across all three cross-

sectional networks. The results of the bootstrapped difference tests for edge weights and EI are shown in **Figure S1**.

Cross-lagged panel networks

The CLPN structures and the corresponding out-EI and in-EI values are shown in Fig. 2. All estimated edge weights derived from the LASSO cross-lagged panel networks are presented in the adjacency matrices in **Tables S5 and S6**. The autoregressive paths are shown in **Figure S2**.

From T1 to T2 (Fig. 2.A), AR showed a strong autoregressive effect and cross-lagged predictive effects on multiple subsequent nodes. The strongest positive effects of AR were observed on SE3, SE4 (“When you experience side effects from it”), and PC5 (“I felt the side effects of the medicine”). The strongest cross-lagged path in the overall network was from SE3 to SE6 (“When you think your sexual partner will get angry about your use of HIV prevention medication”). Figure 2.C shows the out-EI and in-EI values for the T1-to-T2 CLPN. SE3, AR, and SE8 had the highest out-EI values, indicating stronger overall predictive effects on subsequent nodes. SE5 (“When using HIV prevention medication becomes too much of a hassle”), MM1, and SE6 had the highest in-EI values, indicating that they were more strongly influenced by other nodes at the previous time point.

From T2 to T3 (Fig. 2.B), AR again showed a strong autoregressive effect. In addition, AR had its strongest cross-lagged effect on MM2, which was negative, and positive predictive effects on PE4 (“I’m used to taking medicine”) and PC1 (“I worry that the medicine has no effect”). The strongest cross-lagged path in the overall network was from SE4 to SE5. Figure 2.D shows the out-EI and in-EI values for the T2-to-T3 CLPN. The three nodes with the highest out-EI were AR, PE3 (“My fear of AIDS is lessened”), and SE2 (“When you are drinking alcohol or using other drugs”), whereas the three nodes with the highest in-EI were PE4, SE6, and SE3, suggesting that these nodes were particularly prominent in predicting subsequent nodes or being influenced by the prior network. The results of the bootstrapped difference tests for edge weights, out-EI, and in-EI across the 2 CLPNs are presented in **Figure S3**.

Network accuracy and stability

In the cross-sectional networks, the 95% bootstrap confidence intervals for edge weights were generally narrow (**Figure S4**), indicating reliable edge-weight estimation. Similarly, in the cross-lagged networks, the 95% bootstrap confidence intervals were also generally narrow (**Figure S5**), suggesting good accuracy of the edge-weight estimates. The case-dropping bootstrap results showed that the correlation stability coefficients for EI in the T1, T2, and T3 cross-sectional networks were all above 0.50 (**Figure S6**), indicating good stability of the centrality indices. Although the stability of in-EI in the T1-to-T2 CLPN was relatively lower, the centrality indices of both cross-lagged networks were generally acceptable overall (**Figure S7**).

Sensitivity analysis

A total of 410 participants completed both the T1 and T2 follow-up assessments. To assess the robustness of the primary findings, a sensitivity analysis was performed based on this sample. The results showed that the cross-sectional network structures at T1 and T2 and the T1-to-T2 CLPN were largely consistent with the main analysis. Specifically, the major network features, key edges, and node centrality patterns remained similar in both direction and relative strength. The corresponding weighted adjacency matrices and network visualizations are presented in the supplementary material (**Tables S7-S9 and Figures S8-S13**).

Discussion

This study used cross-sectional network analysis and CLPN analysis to systematically examine the dynamic relationships among PrEP adherence, self-efficacy, and risk perception among MSM in western China. The cross-sectional networks showed that, across T1, T2, and T3, the node most strongly and positively associated with PrEP adherence was consistently PE2 (“I can remember to take my medicine on time”). In terms of node centrality, SE3 (“When your sexual partner is upset about your use of it”) showed high importance across time. The longitudinal networks further indicated that PrEP adherence not only exhibited strong autoregressive effects but also predicted multiple subsequent self-efficacy and risk perception nodes. The accuracy, stability, and sensitivity analyses further supported the robustness of these findings.

In the cross-sectional networks, PE2 was consistently the node most strongly and positively associated with PrEP adherence. PE2 reflects individuals’ subjective experience of whether they can remember to take PrEP on time. This finding suggests that PrEP adherence is closely related to individuals’ self-perceived execution of medication-taking behavior. When individuals believe that they can complete medication-taking consistently, they are more likely to show higher actual adherence. From a psychological perspective, this subjective perception may reflect perceived behavioral control and self-regulatory capacity. The Theory of Planned Behavior identifies perceived behavioral control as an important predictor of behavior[44], and self-regulatory processes have likewise been recognized as key mechanisms underlying medication adherence[45]. Accordingly, interventions should focus not only on objectively missed doses, but also on strengthening individuals’ perceived control over regular medication-taking. Digital support strategies such as medication reminders may improve adherence[46], and habit-based support may help promote the transition from externally prompted behavior to stable execution and behavioral automaticity [47].

The centrality results of the cross-sectional networks suggest that the key nodes in the PrEP adherence-related network were not static across time. At T1, the two most influential nodes were SE3 and PE1 (“I believe the medication keeps me safe from HIV”); at T2, they were SE5 (“When using HIV prevention medication becomes too much of a hassle”) and SE3; and at T3, they were SE3 and MI3 (“I do not like the dosage form of the medication”). Notably, SE3 consistently ranked among the most influential nodes, highlighting the sustained importance of partner attitude-related situations in the network. This finding suggests that PrEP adherence is shaped not only by individual factors, but also by intimate relationships,

social evaluation, and stigma-related contexts, consistent with previous studies[19, 48, 49]. Stage-specific patterns were also evident. At T1, PE1 ranked second in importance, suggesting that early recognition of PrEP's protective benefits may be an important perceived benefit, consistent with the Health Belief Model[50]. This highlights the value of strengthening education on PrEP effectiveness and benefits during initiation. At T2, SE5 emerged as the most influential node, indicating that medication burden and daily management demands may become more prominent during the maintenance phase. Consistent with previous research, accumulated burden and inconvenience may undermine adherence[51, 52]. Simplifying follow-up procedures and optimizing medication reminders may therefore help reduce barriers to continued use. At T3, MI3 became the second most influential node, suggesting that the subjective experience of the medication itself may play a greater role at later stages. This underscores the need to attend to the experiences of long-term users and, where feasible, provide individualized support. Overall, these findings suggest that the core factors in the PrEP adherence-related network change across stages of use, highlighting the need for dynamically tailored interventions.

The longitudinal networks showed that PrEP adherence had strong autoregressive effects, suggesting temporal stability and behavioral inertia. From a behavioral psychology perspective, repeatedly performed behaviors may gradually become more automatic, consistent with habit formation theory [53]. More importantly, PrEP adherence was not merely an outcome shaped by other psychological and behavioral factors, but also predicted multiple subsequent self-efficacy and risk perception nodes, suggesting sustained bidirectional dynamics between adherence behavior and psychological factors. This finding is consistent with reciprocal determinism in social cognitive theory, which posits that behavior, cognitive factors, and context interact and shape one another over time[12]. It may also be understood as an ongoing self-regulatory feedback process, in which medication-taking experience is influenced by prior cognitions and, in turn, reshapes subsequent cognition and behavioral maintenance[54]. Previous HIV treatment research has likewise shown continuing interactions among adherence, self-efficacy, and provider-related factors[55], while longitudinal PrEP studies have shown that adherence follows distinct trajectories and is influenced by modifiable psychological and behavioral factors[27]. Taken together, these findings suggest that PrEP adherence is not only a behavioral outcome, but also an important driver of the subsequent psychological system, providing a dynamic perspective on its development and maintenance.

The CLPN results further showed that the key pathways within the PrEP adherence-related system were stage-specific, suggesting that intervention priorities may differ across phases of use. From T1 to T2, AR showed strong positive predictive effects on SE3, SE4 ("When you experience side effects from it"), and PC5 ("I felt the side effects of the medicine"). This suggests that early adherence is not only an outcome, but may also shape individuals' subjective experiences of PrEP use, consistent with the "behavior–cognition–environment" interaction framework proposed in medication experience research[56]. These findings highlight the importance of partner communication support, side-effect expectation management, and stigma-related counseling during the early initiation phase. From T2 to T3, AR positively predicted PE4 ("I'm used to taking medication") and PC1 ("I worry that the medicine has no

effect”), but negatively predicted MM2 (“I trust the doctors here”). This suggests that later adherence may reflect a maintenance process more closely related to habit formation, sustained burden, and reappraisal of the healthcare relationship. Although continued medication use may gradually foster habit formation, long-term use does not necessarily imply complete stability, as individuals may still develop new concerns about treatment effectiveness and medical relationships. Accordingly, interventions during the maintenance phase should place greater emphasis on sustained motivational support, explanation of PrEP effectiveness, continuity of care, and person-centered service delivery. Previous studies have likewise suggested that PrEP support strategies should be dynamically tailored to stage of use, risk context, and long-term adherence needs[57, 58].

Limitations

This study has several limitations. First, given the specific characteristics of the study population, non-probability sampling was used. In addition, the primary analysis adopted a complete-case approach and included only participants who completed all three follow-up waves (T1, T2, and T3). Although this approach provided a balanced longitudinal dataset suitable for CLPN analysis, it may have introduced attrition-related selection bias or adherence-related bias. Therefore, the representativeness of the sample and the generalizability of the findings may be limited. Second, adherence was measured using self-reported data. Although self-reported measures are widely used in adherence research[59, 60], they may be affected by recall bias and social desirability bias, potentially leading to overestimation. Third, although this study used both cross-sectional network analysis and CLPN analysis and assessed the robustness of the findings through stability, accuracy, and sensitivity analyses, network analysis is primarily intended to identify patterns of associations among variables and cannot support causal inference. Although CLPN analysis provides temporally ordered predictive information, findings based on observational data cannot be interpreted as strict causal effects[61]. Future studies with larger samples, more representative populations, objective adherence measures, and more comprehensive missing-data strategies are needed to further validate these findings.

Conclusion

This study examined the dynamic relationships among PrEP adherence, self-efficacy, and risk perception among MSM in western China. To our knowledge, this is the first study to use CLPN analysis to investigate the dynamic interplay among these three constructs at the item level. The findings suggest that PrEP adherence is not merely a behavioral outcome, but part of a stage-specific and directional dynamic system involving multiple psychological and behavioral components. Factors such as remembering to take medication on time, partner-related situations, medication burden, perceived protection, and medication experience showed varying importance across stages. PrEP adherence was influenced by self-efficacy and risk perception, and in turn predicted subsequent psychological and behavioral components. These findings provide a more systematic understanding of the development and maintenance of PrEP adherence among MSM and may help identify more precise intervention targets and inform the optimization of targeted PrEP intervention strategies.

Abbreviations

Abbreviation	Full term
HIV	Human immunodeficiency virus
MSM	Men who have sex with men
PrEP	Pre-exposure prophylaxis
ART	Antiretroviral therapy
CLPN	Cross-lagged panel network
GGM	Gaussian graphical model
LASSO	Least absolute shrinkage and selection operator
EBIC	Extended Bayesian information criterion
EI	Expected influence
Out-EI	Out-expected influence
In-EI	In-expected influence
CI	Confidence interval
CS-C	Correlation stability coefficient

Declarations

Ethics approval and consent to participate

Our study was conducted in accordance with the Declaration of Helsinki. The study protocol was approved by the Ethics Committee of Chongqing Medical University (Reference number: 2019001). Before participation, all participants were fully informed about the purpose, significance, voluntary participation, and confidentiality of the research. Each participant signed an informed consent form.

Consent for publication

Not applicable.

Availability of data and materials

For the privacy of MSM population, the dataset supporting the conclusion of this article is available upon reasonable request from the corresponding author.

Competing interests

The authors declare no competing interests.

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Authors' contributions

Xiaoni Zhong and Bing Lin were responsible of the conception and design of the study. Yuxin Xie, Hao Tan, Hong Chen, and Qin Qin were in charge of the analysis and interpretation and the data collection process. All authors were involved in the drafting of the manuscript and critically reviewed it for important intellectual content. All authors gave their approval on the final version to be published and agreed to be accountable for all aspects of the work.

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of Joint United Nations Pro-gramme on HIV/AIDS (UNAIDS).

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Figures

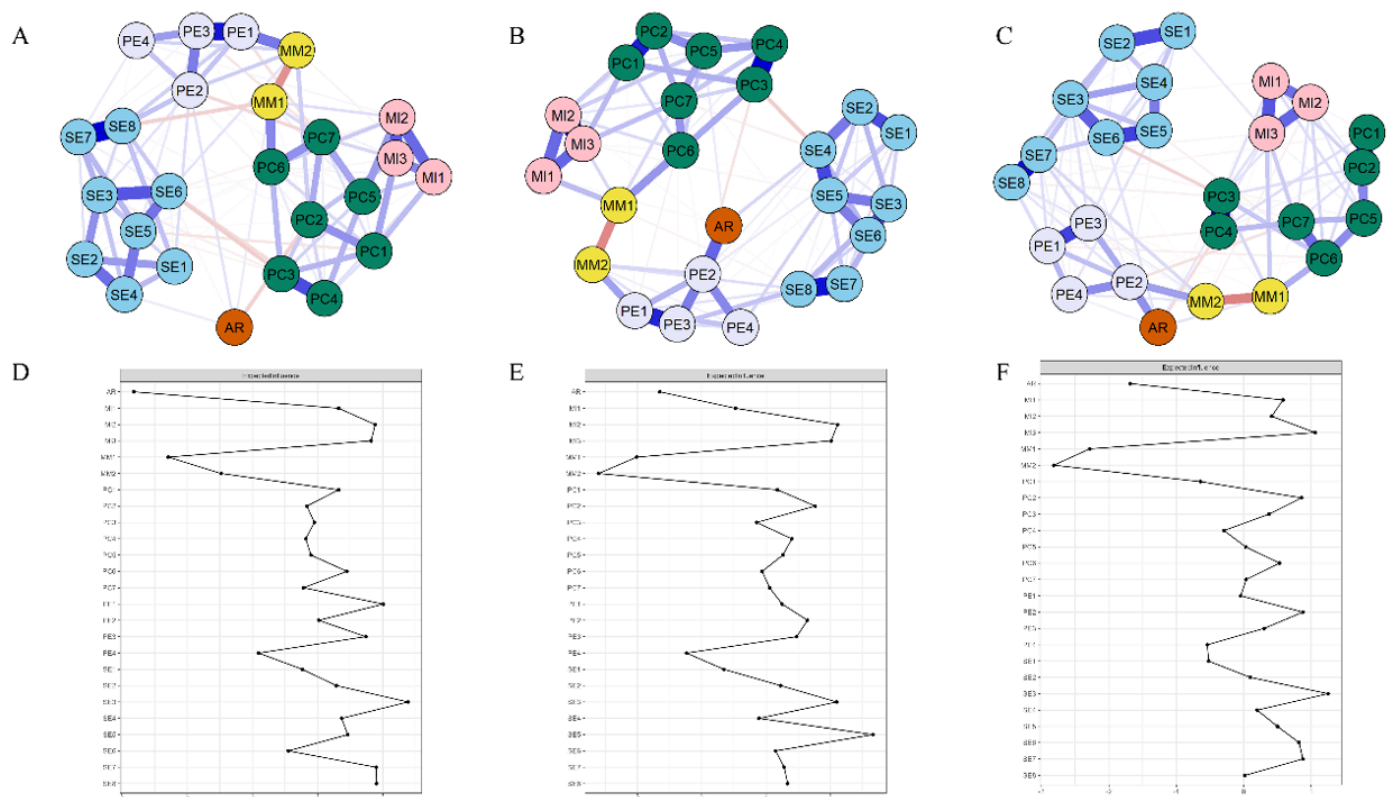


Figure 1

Cross-sectional network structures at T1 (A), T2 (B), and T3 (C), and expected influence centrality indices of all items at T1 (D), T2 (E), and T3 (F).

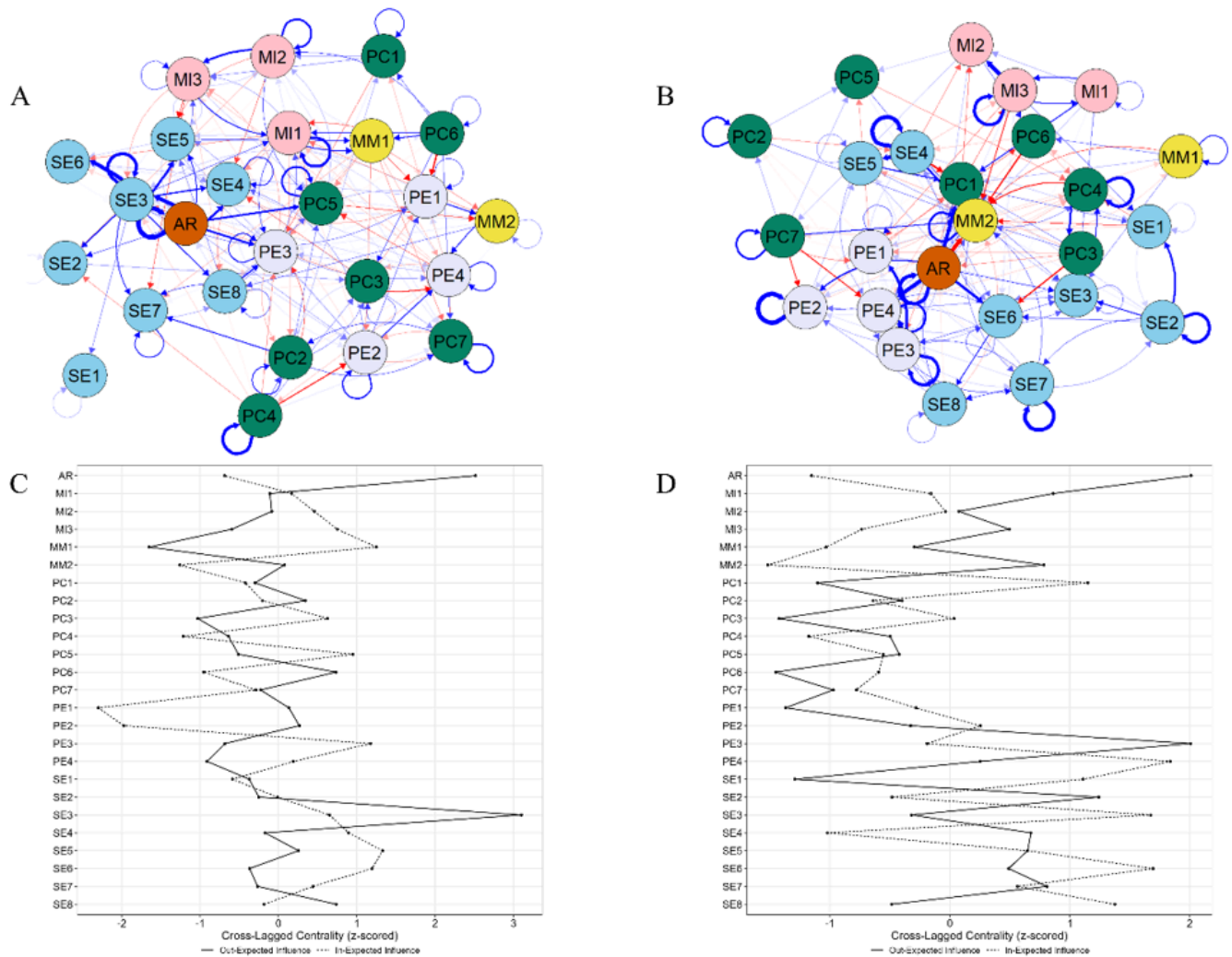


Figure 2

Cross-lagged panel network structures at T1–T2 (A) and T2–T3 (B), and out- expected/in-expected influence centrality indices at T1–T2 (C) and T2–T3 (D).

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