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Development and Expanded Clinical Applications of the Da Vinci Surgical Robot System in High-Altitude Regions of Mongolia

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ABSTRACT

Research Context: The high-altitude conditions in Mongolia (average elevation: 1580 meters), characterized by diminished atmospheric pressure, lower temperatures, and reduced oxygen concentration, present operational challenges for the Da Vinci Surgical System. These environmental factors induce power output attenuation in robotic actuators, measurement deviations in sensing components, and compromised thermal management performance. Such technical constraints underscore the imperative for system-level adaptations to ensure the operational precision and procedural safety required for minimally invasive robotic surgery in plateau environments.

Research Methodology: (1) The high-altitude-adapted dynamics optimization model for robotic manipulators.(2) barometric compensation algorithm development. (3) systematic formulation of governing equations for cryogenic-resistant material systems and hierarchical thermal dissipation architectures.

Research Outcomes:Manipulator Dynamics Model:$M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}+G(\theta)=\tau-D(\dot{\theta})\theta$.Barometric Compensation Algorithm:$PV=nRT \Rightarrow V_{comp}=V_0P_0/P$. Cryogenic Lubrication and Thermal Management Equations:$Q_{gen}=Q_{cond}+Q_{conv}+Q_{rad}+Q_{cooling}$.

Research Conclusions: This study theoretically validates the operational feasibility of the Da Vinci Surgical System in Mongolia's high-altitude environments (average 1,580m). The optimized manipulator dynamics, sensor stabilization protocols, and adaptive thermal management systematically demonstrate compliance with plateau surgical requirements, establishing a technical framework for upgrading intelligent surgical equipment in elevated terrains. The deep integration of 5G communication and artificial intelligence (AI) drives cross-disciplinary innovations in clinical application.Clinical Advancements:General Surgery: Cholecystectomy, colorectal tumor. resectionUrology: Radical prostatectomy, partial nephrectomy.Gynecology: Hysterectomy, endometriosis management.Cardiothoracic Surgery: Valvuloplasty, pulmonary procedures.Orthopedics: Articular and spinal interventions.

Keywords: *Clinical Applications, Da Vinci Surgical System, Expansion, High-Altitude Regions, Mongolia, Surgery.*

1. INTRODUCTION

Robotic Surgical System Architecture in Mongolian Plateau Environments.The Da Vinci Surgical System in high-altitude Mongolia comprises three subsystems: surgeon console, robotic manipulators, and stereoscopic imaging [1]. Robotic Manipulator System:Featuring 3-4 modular arms with 7-DoF (degrees of freedom) endoscopic instruments, the system surpasses conventional laparoscopy (4-5 DoF). A compact configuration integrates one laparoscope arm with four instrument arms, enabling multi-quadrant minimally invasive surgery (MIS) via 5G-enabled teleoperation [2,4].Surgeon Console:Operators utilize ergonomic master controls with 3D stereoscopic visualization (≥10× magnification) to execute procedures like tissue dissection and suturing. The intuitive interface reduces cognitive load through motion scaling (e.g., 1:0.5 ratio) and tremor filtration [5,7]. Enhanced Imaging Subsystem:Dual-lens stereocameras generate depth-perceptive 3D visualization critical for tissue stratification and neurovascular identification, particularly in oncological demarcation. Clinical studies confirm improved surgical precision ($p<0.05$) attributed to this imaging superiority [3,6].

2. METHODOLOGY.

An optimized dynamic model for robotic arm manipulation was developed through mechanical and physical principles. The thermodynamic regulation system was engineered based on energy conservation laws to maintain cryogenic stability for sensory components and actuation mechanisms in da Vinci surgical platforms. Fundamental design methodologies were established through integration of barometric compensation algorithms, cryogen-compatible tribological materials, and enhanced thermodynamic dissipation architectures.

3. RESULTS.

3.1 Formulation of Robotic Arm Dynamics Model for Elevated Terrain.

Framework of Model Principles for Special Requirements of Da Vinci Robotic Surgical System in High-altitude Regions of Mongolia.The development of the high-altitude robotic arm dynamics model employs Lagrange equations, incorporating altitude-induced gravitational variations and potential aerodynamic resistance effects. This analytical approach accounts for atmospheric parameter deviations characteristic of plateau environments, particularly addressing the reduced air density and its impact on motion control precision.

3.1.1 In high-altitude regions, the Lagrangian function of the Da Vinci robot [8] .

$\mathbf{L = K - P}$ ①

K:The total kinetic energy. P:the total potential energy.

3.1.2 Calculation of the kinetic energy of the Da Vinci robot in high-altitude regions.

3.1.2.1 The kinetic energy of each link includes translational kinetic energy and rotational kinetic energy.

$Ki=1/2mi\mathbf{v}^{\mathbf{T}}i\mathbf{v}i + 1/2\omega^{T}i\mathbf{I}i\omega i,$ 、 ②

3.1.2.2 The total kinetic energy。

$\mathbf{K}=\sum_{i=1}^{\mathbf{n}} \mathbf{K}\, i$ ③

$\mathbf{v}_i=\mathbf{J}_{vi}(\theta)\dot{\theta}$, $\omega_i=\mathbf{J}_{\omega i}(\theta)\dot{\theta}$,The Jacobian matrices $\mathbf{J}_{vi}$ and $\mathbf{J}_{\omega i}$ describe the relationship between the link velocities and the joint velocities.

3.1.3 Potential energy calculation for the Da Vinci robot in high-altitude areas.

3.1.3.1 Potential energy of each link in the Da Vinci robotic arm.

$\boldsymbol{Pi=mighi(\theta)}$ ④

3.1.3.2 Total potential energy.

$\boldsymbol{P}= \sum_{i=1}^{n} Pi$ ⑤

3.1.3.3 Gravity acceleration correction equation at high altitude.

$\boldsymbol{g'=g(R/R+h)^2}$ ⑥

R:Radius of the earth. H：Altitude.

3.1.4 Dynamic equations of the Da Vinci robot in high-altitude regions; derived via Lagrange's equations.

$\mathbf{d/dt(\partial L/\partial \dot{\theta}_j)-\partial L/\partial \theta_j=\tau_j+\tau ext,}_{\mathbf{j}}$ ⑦

L=K−P:Lagrangian (kinetic energy K minus potential energy P).$\boldsymbol{\theta_j}$:Generalized coordinates (Joint angles).$\boldsymbol{\tau_j}$:Joint driving force/torque.$\boldsymbol{\tau ext,_j}$:External generalized force (such as air resistance, external force disturbance).

3.1.4.1 .Standard equations for the dynamics of the Da Vinci robot at high altitude.

$\mathbf{M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}+G(\theta)=\tau+\tau ext}$ ⑧

$\mathbf{M(\theta)\ddot{\theta}}$ ：Force of inertia. $\mathbf{C(\theta,\dot{\theta})\dot{\theta}}$ ：Velocity dependent. $\mathbf{G(\theta)}$ ：Gravity. Total applied force=**τ** (Driving force)+**τext** (External force)

3.1.4.2 Inertia Matrix.

$$\mathbf{M(\theta)}=\sum_{i=1}^{n}(m_i\mathbf{J}^{\mathbf{T}}{}_{vi}\mathbf{J}_{vi}+\mathbf{J}^{\mathbf{T}}{}_{\omega i}\mathbf{R}_i\mathbf{I}_i\mathbf{R}^{\mathbf{T}}{}_i\mathbf{J}_{\omega i})\ ⑨$$

M(θ): Generalized inertia matrix, dependent on joint angles θ. $\mathbf{m}_i$**:** Mass of the $_i$-th link. $\mathbf{J}_{vi}$, $\mathbf{J}_{\omega i}$**:** Translational and rotational Jacobian matrices for the $_i$-th link, respectively. $\mathbf{R}_i$**:** Rotation matrix mapping the $_i$-th link's local frame to the base frame. $\mathbf{I}_i$**:** Inertia tensor of the $_i$-th link expressed in its local coordinate system. **T:** Superscript denoting matrix transpose.

3.1.4.3 Coriolis [9] and centrifugal matrices $\mathbf{C(\theta,\dot{\theta})}$。

$$\mathbf{C}_{jk}=\sum_{i=1}^{n}1/2(\partial\mathbf{M}_{jk}/\partial\theta_i+\partial\mathbf{M}_{ki}/\partial\theta_j-\partial\mathbf{M}_{ij}/\partial\theta_k)\dot{\theta}_i\ ⑩$$

θ: Joint position vector (generalized coordinates).$\mathbf{\dot{\theta}}$**:** Joint velocity vector.**M(θ)**: The mass matrix (or inertia matrix) of the system, which is symmetric and positive definite and depends on **θ**.$\mathbf{C}_{jk}$:The J-th row and K-th column elements of the Coriolis and centrifugal matrices.

3.1.4.4 The gravity term **G(θ).**

$$\mathbf{G(\theta)}=\sum_{i=1}^{n}\mathbf{m}_i\mathbf{g'}\partial\mathbf{h}_i/\partial\theta\ ⑪$$

3.1.4.5 External moment of force, **τext**（air resistance）.

$\mathbf{\tau ext=-D(\dot{\theta})\dot{\theta}}$ ⑫

Text: External torque due to air resistance (or other environmental forces). $\mathbf{D(\dot{\theta})}$**:**Damping matrix, representing velocity-dependent resistance effects. $\mathbf{\dot{\theta}}$**:**Joint angular velocity vector (e.g., velocities of robotic arm joints or drone rotors). **−:**Indicates that the damping torque opposes the direction of motion, dissipating energy.The damping matrix **D** decreases with decreasing air density (high altitude).

3.1.5 Equation ⑬ of the optimized dynamics model equation of the manipulator arm of Da Vinci robot at high altitude is proved and established by①②③④⑤⑥⑦⑧⑨⑩⑪⑫**.**

$\mathbf{M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}+G(\theta)=\tau-D(\dot{\theta})\dot{\theta}}$ ⑬

Key adjustment parameters: gravity acceleration **g '** was corrected by altitude. The air resistance term **D** is adjusted with the air density.

3.2 The sophisticated temperature control system of the Da Vinci robot in high-altitude regions maintains the operation of sensors and transmission devices under low-temperature conditions.

3.2.1 When designing the sophisticated temperature control system for the Da Vinci robot in Mongolia's high-altitude regions, comprehensive consideration must be given to thermodynamics, heat transfer, and control theory.

3.2.1.1 The heat conduction equation of the Da Vinci robot in high-altitude regions.（Fourier's Law[10]）.

$\mathbf{Qcond=-kA\Delta T/\Delta x}$ ⑴

Significance: Calculating the thermal conduction efficiency within the device.**k**: Thermal conductivity of the material (W/m·K).**A**: Cross-sectional area for heat transfer (m^2).**ΔT/Δx**: Temperature gradient (K/m).**High-altitude impact**: High thermal conductivity materials must be selected to compensate for potential heat dissipation efficiency reduction.

3.2.1.2 The thermal convection equation of the Da Vinci robot in high-altitude regions.（Newton's Law of Cooling[11]）.

$\mathbf{Qconv=hA(T_8-T_{amb})}$ ⑵

Significance: Evaluating natural or forced convection heat dissipation capacity. **h**: Convective heat transfer coefficient ($W/m^2 \cdot K$).**T8**: Surface temperature (K).**Tamb**：Ambient temperature (K).

High-altitude modification: Rarefied air reduces the convective heat transfer coefficient (h), necessitating forced convection or increased heat transfer surface area.

Nusselt number correlation (natural convection)：**$Nu=C(Gr\ Pr)^n$**(3)

Glachev number:$Gr=g\beta\Delta TL^3/\nu^2$, Prandtl number: $Pr=\nu/\alpha$.

3.2.1.3 Thermal radiation equation of Da Vinci robot at high altitude.（Steffan-boltzmann law[12]）.

$Qrad=\epsilon\sigma A(T^4_8-T^4_{amb})$ (4)

Significance: calculate radiation heat dissipation power.ϵ：Surface emissivity. σ：Steffan-boltzmann constant（5.67×10^{-8} W/m^2K^4）. High altitude application: the proportion of radiation heat dissipation may increase in low temperature environment.

3.2.1.4 It is proved by (1)(2)(3)(4) that the heat dissipation balance equation (steady state condition) of Da Vinci robot at high altitude is established (5).

Qgen=Qcond+Qconv+Qrad+Qcooling (5)

Significance: system heat production (sensor/transmission device) and total heat dissipation balance.

Qgen: Equipment heat generation power (W). **Qcooling:**Cooling power of a temperature control system such as TEC.

3.2.1.5 Thermoelectric cooling (TEC) equation for Da Vinci robot at high altitude[13].

$Qc=\alpha IT_c-1/2I^2R-K\Delta T$ (6)

Significance: Calculate the heat absorption at the cold end of thermoelectric refrigerators.Qc：Refrigerating capacity. α：Seebeck coefficient（V/K）. I：Current (A). T_c：Cold end temperature（K）. R：Resistance of the thermoelectric arm（Ω）. K：Thermal conductivity（W/K）. ΔT：Temperature difference between hot and cold ends.

Application: For active refrigeration, current needs to be optimized to balance efficiency and temperature difference.

3.2.1.6 Transient heat capacity equations for Da Vinci robot at high altitude[14].

Q=mcdT/dt (7)

Significance: To analyze the course of temperature change over time. **m**：Quality of equipment（kg）. **c**：Specific heat capacity.（J/kg·K）. dT/dt：Rate of change in temperature（K/s）.

3.3.1.7 PID control equations for Da Vinci robot at high altitude[15].

$u(t)=K_pe(t)+K_i\int^t_0e(\tau)d\tau+K_dde(t)/dt$ (8)

Significance: Dynamic adjustment of temperature control system output of Da Vinci robot at high altitude.

e(t)=Tset−Tactual:Error in temperature.

K_p,K_i,K_d: Proportional, integral, differential gain.

3.3.1.8 Key Design Considerations for Temperature Control System of Da Vinci Robot in Mongolia's.

High-Altitude Regions to Maintain Sensor and Actuator Performance Under Low-Temperature Conditions.For high-altitude low-temperature thermal control systems, core strategies include: Implementing forced convection or expanding heat dissipation area to offset convective efficiency attenuation. Applying high-emissivity coatings to enhance radiative heat dissipation. Selecting redundantly designed TEC modules, optimizing material parameters and thermal performance, and integrating adaptive control algorithms for dynamic adjustments. By enhancing heat sink efficiency, optimizing COP selection, and tuning PID parameters, efficient thermal management under extreme operating conditions is achieved, alongside simulation verification and experimental testing. Key objectives include balancing convective losses, ensuring thermal stability under extreme conditions, and reducing system energy consumption.

3.3 Integrated pressure compensation algorithm for Da Vinci robot at high altitude.

3.3.1 Atmospheric pressure P varies with altitude h at high altitudes and is described by the simplified barometric

height formula.

$P=P0(1-L\cdot h/T0)^{g\cdot M/R\cdot L}$ (I)

P0: Standard atmosphere at sea level（101325 Pa）. **L**：Temperature lapse rate（0.0065 K/m）. **T0:**Sea level standard temperature（288.15 K.）. **g**：Acceleration of gravity (9.80665 m/s²). M：Dry air molar mass (0.028964 kg/mol). R：General gas constant (8.314 J/ mol·K)).

Purpose: To calibrate pressure sensors and compensate for absolute pressure changes caused by altitude.

3.3.2 Gas volume compensation at high altitude (ideal gas law correction). The volume control of pneumatic components (such as cylinders) should compensate for air pressure changes and correct the ideal gas law[16].

$P\cdot V=nRT\Rightarrow V_{comp}=V0P0/P$ (II)

V_{comp}: Compensated volume. **V0**: Volume at standard pressure. **P:** Current pressure.

Purpose: To ensure the output force of the pneumatic actuator remains consistent between high altitude and low altitude.

3.3.3 Fluid flow control (Bernoulli equation), the flow rate Q in the liquid pipeline is affected by the pressure, and the Bernoulli equation needs to be modified[17].

$Q=A\cdot\sqrt{(Ppump-Patm)/\rho}$ (III)

A：Sectional area of pipeline.**P_{pump}**：Pump output pressure. **P_{atm}**：Local atmospheric pressure. **ρ**：Density of fluid.

Purpose: To maintain a steady flow rate of liquids (e.g., perfusion systems).

3.3.4 The output Fraw of the Da Vinci robot sensor compensation and strain gauge sensor at high altitude compensates for the zero drift caused by air pressure.

$F_{comp}=F_{raw}-k\cdot(P0-P)$ (IV)

Fraw: The raw/uncompensated output force measured by the Da Vinci robot's sensor (e.g., strain gauge sensor) before compensating for air pressure effects. At high altitudes, lower air pressure can cause "zero drift" (a baseline shift in sensor readings even when no external force is applied), which this formula aims to correct.

Fcomp: The compensated output force after adjusting for zero drift caused by air pressure differences.This value represents the "true" force feedback at the robotic arm's end, ensuring accuracy across varying altitudes.

K:Sensor pressure sensitivity coefficient (obtained by calibration).

Application: Critical for medical or precision robotics (like the Da Vinci system) where reliable force feedback is essential for safe and accurate operation, even in environments with significant air pressure variations.

3.3.5 For the Da Vinci robot's sealed cavity pressure balance in high-altitude regions.If the robot contains a sealed cavity (e.g., the motor compartment of the Da Vinci robot), the internal pressure **P_{int}** must be dynamically balanced.

$P_{int}=P_{ext}+\Delta P_{design}$(V)

P_{ext}: External ambient pressure. **ΔP_{design}**：Design differential pressure.

Purpose: To prevent structural deformation or seal failure.

3.3.6 Dynamic Air Pressure Filtering (Real-Time Noise Suppression) for the Da Vinci Robot in High-Altitude Regions **Praw(t).**

$P_{filtered}(t)=\alpha\cdot P_{raw}(t)+(1-\alpha)\cdot P_{filtered}(t-1)$ (VI)

$P_{raw}(t)$: Raw pressure signal at time **t**, directly from the sensor.**$P_{filtered}(t)$:**Filtered pressure signal at time t, after noise suppression.**$P_{filtered}(t-1)$:**Previous filtered value (at time t−1).**α**：filtering coefficient (depends on sampling frequency and noise characteristics).Purpose: Eliminate high frequency noise caused by airflow disturbance.

3.4 Enhanced Heat Dissipation Design of Low-Temperature Lubrication Materials for Da Vinci Robots in High-Altitude Regions.

3.4.1 Modeling the Characteristics of Low-Temperature Lubrication Materials for Da Vinci Robots in High-Altitude Regions [18].

3.4.1.1 Viscosity-Temperature Characteristics of Lubricants for Da Vinci Robots in High-Altitude Regions [19] .

(Vogel-Fulcher-Tammann Equation)

$\mu(T)=\mu_\infty \exp(B/T-T0)$ (①) $\mu(T)$：

Dynamic viscosity at temperature **T**.

μ_∞,B,T0：Material fitting parameters.

Purpose: To predict the effect of low temperature on the fluidity of lubricants and avoid mechanical stuck due to high viscosity.

3.4.1.2 Low temperature friction coefficient correction of Da Vinci robot at high altitude.

$f(T)=f_0[1+\alpha(T_{ref}-T)]$ (②)

f_0：Friction coefficient at the reference temperature **T_{ref}**.

α：Friction temperature sensitivity coefficient.
Purpose: To quantify the effect of low temperature on friction of moving parts.

3.4.2 Enhanced heat dissipation design equation for Da Vinci robot at high altitude.

3.4.2.1 Convective heat dissipation correction of Da Vinci robot in high altitude area [20]. The natural convection coefficient hconv at low pressure needs to be corrected.

$h_{conv}=h_0(P/P_0)^n(T_{surface}-T_{ambient}/T_0)^m$ (③)

h_0: Convection coefficient at standard pressure.

n,m：The exponents related to the flow regime (n≈0.5, m≈0.25 for laminar flow).

Purpose: To quantify the reduction in heat dissipation efficiency caused by thin air.

3.4.2.2 The radiation heat dissipation of Da Vinci robot at high altitude is enhanced (Stefan-Boltzmann law [12]), which is the same as the above equation⑷.

3.4.2.3 Equivalent thermal conductivity of heat pipe of Da Vinci robot in high altitude area [21].

$k_{eff}=Q\cdot L/A\cdot\Delta T$ (④)

L: length of heat pipe. **ΔT:** temperature difference between the two ends of the heat pipe.

3.4.3 Thermo-mechanical coupling stability analysis of Da Vinci robot at high altitude.

3.4.3.1 Material thermal stress equation of Da Vinci robot in high altitude area [22].

$\sigma_{thermal}=E\cdot\alpha T\cdot(T_{operate}-T_{install})$ (⑤)

$\sigma_{thermal}$: Thermal Stress.**E:** modulus of elasticity. **αT:** coefficient of thermal expansion.**$T_{operate}-T_{install}$:**Temperature Difference.**$T_{operate}$:** The actual operating temperature of the structure (°C).**$T_{install}$:**The installation or initial temperature of the structure (°C).

Purpose: To prevent the structural stress over-limit caused by low temperature contraction.

3.4.3.2 Interface contact thermal resistance of Da Vinci robot at high altitude.

$R_{contact}=1/h_c\cdot A+\delta/k_{gap}\cdot A$ (⑥)

h_c：Contact conduction coefficient. **δ**：Thickness of the interface gap.**k_{gap}**：Thermal conductivity of gas/filler in the gap.

Purpose: Optimize the mechanical connection interface to reduce thermal resistance.

3.4.4 A dynamic thermal management control algorithm for a Da Vinci robot at high altitude.

3.4.4.1 PID temperature control model of Da Vinci robot in high altitude area[15], same as the above equation ⑻.

3.4.4.2 Dynamic thermal load distribution of Da Vinci robot in high altitude areas [23].

$\sum Q_{dissipated}\geq Q_{generated}=\sum$（$f\cdot Fn\cdot v+I\cdot I\cdot R$）(⑦)

$Q_{generated}$：Total heat production, including mechanical friction (sliding friction work) and electrical losses (Joule heat).

$\sum Q_{dissipated}$：Total heat dissipation, including convection, radiation, conduction and other paths of the sum of heat dissipation capacity.

f：Friction coefficient (To be modified at low temperature, see **f(T)** equation above: **(②)**). Fn：Contact surface normal force (related to mechanical load). v：Sliding speed (relative speed of moving parts).**I:** Motor current.**R:** Resistance (electrical component characteristics).

Purpose: To ensure that the heat dissipation capacity covers the mechanical friction and motor heat generation.

4. DISCUSSION.

4.1 Clinical Application of Da Vinci Robotic Surgery in Mongolia's High-Altitude Regions.

Mongolia's high-altitude environment necessitates optimized robotic arm dynamics to account for atmospheric pressure variations [24]. A pressure compensation algorithm adjusts the arm's dynamic response for low-pressure conditions [25], while cold-resistant materials ensure stability in extreme temperatures [24]. Additionally, a gradient-based thermal management system maintains efficient heat dissipation [25]. These integrated optimizations can enhance the Da Vinci system's performance in Mongolia's harsh environment.

4.2 Key Advantages in High-Altitude Surgery.

Precision: Robotic arms outperform human hands in confined spaces (e.g., neurovascular dissection).Minimally Invasive: Reduced trauma, bleeding, and recovery time.Human-Machine Collaboration: Surgeon-led decision-making; robots act as "enhanced tools" without autonomy. 5G and AI-Enhanced Applications:Procedures include cholecystectomy, tumor resection, prostatectomy, nephrectomy, hysterectomy, cardiac valve repair, and pulmonary surgery.

5. CONCLUSION.

Theoretical analysis confirms that the Da Vinci robotic system can adapt to Mongolia's high-altitude conditions, meeting surgical requirements such as robotic arm precision, sensor stability, and thermal performance. This provides a technical framework for upgrading intelligent surgical equipment in high-altitude regions.Integrating 5G communication and AI technologies, the Da Vinci surgical system enables interdisciplinary advancements in clinical fields, including general surgery, urology, gynecology, cardiothoracic surgery, and orthopedics. By translating surgeons' inputs into high-precision movements and combining enhanced vision with intelligent control, the system revolutionizes minimally invasive surgery. It serves as a human-machine collaborative tool—not a replacement for surgeons—with the core goal of improving procedural control and outcomes while minimizing trauma.

Conflict of Interest Statement.

All authors of this paper declare that they have no conflicts of interest.

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Author Contributions and Data Sources.

LC-Manuscript editing and Design.

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Hongxing Hai- Manuscript editing and Data acquisition.

Batbold B- Manuscript editing and Data analysis.

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