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A Novel Investigation and Comparative Study on Building Integrated Photovoltaic Thermal (BIPVT) System

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Abstract
An analysis of BIPVT system has been carried out in this paper based on arrays named as solar cell tile array and semi-transparent array. Previously comparisons and performance analysis were carried out for opaque and semitransparent system in non-optimized way but in the present case it has been optimized to get better results. As far as energy efficiency and exergy is concerned semitransparent PVT has an edge as compared to others in all respect. Semitransparent PVT has higher useful energy gain by 2.5 KWH as compared to SCT. Further the electrical and thermal efficiency has been derived and a conclusion has been made that semitransparent PV cell has an edge in all respects as compared to SCT. The electrical efficiency has been increased to 17.17% from the previous 16% and overall exergy to 18.4% from previous 17.1%. i.e. an overall growth of 6.8% and 7.6% respectively.

Keywords-SCT & semitransparent PVT array, Building integrated photovoltaic system (BIPVT), Photovoltaic (PV), Exergy.

1. Introduction

In recent times solar thermal systems are widely used, but PVTs are not used extensively. More than 80% of the incoming solar energy is either reflected or absorbed as heat energy. Loferski et al. (1998) studied and obtained few results related to the system with air circulation in a housing. Agrawal and Tiwari (2009) concluded that in terms of energy saving glazed hybrid gives better result as compared to normal PV module. Vats and Tiwari (2012) provided various data of the efficiency of different types of material out of which one can select. He et al. (2006) used the Hybrid Photovoltaic and Thermal (PVT) collector technology using water as the coolant as a solution for improving the energy performance. The BIPVT system designed by (Agrawal and Tiwari, 2010) have shown that the roof top placed in an effective area of 65 m^2, is capable of producing the net electrical and thermal exercise of 16,300 kWh and 1550 kWh, respectively, at an overall thermal efficiency of 54.2%. Kim and Kim (2012) have studied simulation of air-type building-integrated photovoltaic-thermal system. Singh et al. (2015) described the modeling and optimization of single channel system by genetic algorithm. The scheme proposed by Singh et al. (2016) made a comparative study of exergy of different cities and concluded that there is an increment of 5.8 to

14.7% of exergy as compared to proposed by Agrawal and Tiwari (2012) using soft computing technique.

2. Thermal Modeling of BIPVT System

In the current paper research has been made on cold climatic condition of India by placing the designed model on the roof top of the building. Rajoria et al. (2012) described the overall energetic heat gain and exergy heat gain and overall efficiency of different city for summer condition.

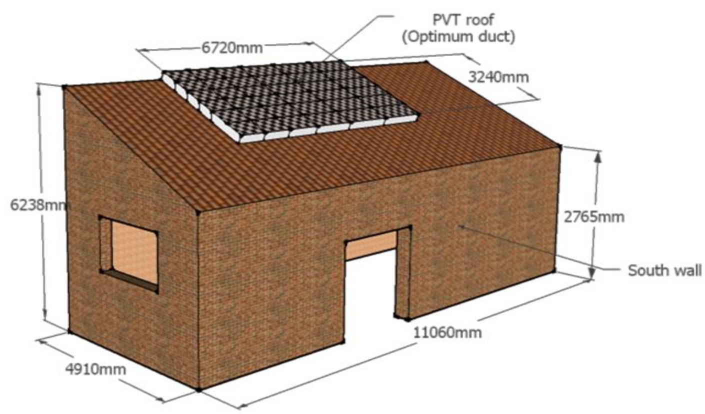

Figure 1. Perspective view of proposed building integrated photovoltaic thermal (BIPVT) system installed at the roof of the building

Rajoria et al. (2013) made an attempt to analyse the performance of semi-transparent hybrid photovoltaic thermal double pass facades (HPVT-DPF) connected in series and parallel in terms of energy and exergy for four weather conditions of Srinagar. Figure 1 shows the prospective view of the designed model with specification of the proposed system. As Srinagar is located at 3401'N, $74^0$51'E due to which the propose systems is fitted in the south direction inclined at an angle of the latitude of that city i.e. 35^0 to the horizontal. With proposed area of 65 m^2 the present system has 48 PV Module in 6rows.

Table 1. Specification of proposed system

V_{max}	425V
η	17.1%
Size of room	5580mm × 4910 mm
Side wall height	2765mm × 6238 mm
Roof area	11060 mm × 6144 mm
Roof inclination	35^0

Table 1 gives the detail specification of the output voltage and room specification.

Table 2. Design parameters of proposed system

Design parameters	Corresponding values
Length of proposed system	1650 mm
Width of proposed system	800 mm
Net output	155 W
Depth of propose Duct	255 mm
channel	single pass channel
C_{air} (J/kg K)	1005
C_r	0.38
h_0 (W/m^2)	5.70 + 3.8 × V_a
h_i (W/m^2)	2.8
h_T (W/m^2)	2.80 + 3 × vair
K_c (W/m^2)	0.040
K_G (W/m^2)	0.80
K_i (W/m^2)	0.0350
K_T (W/m^2 K)	0.380
L_c (mm)	0.3
L_G (mm)	34
L_i (mm)	11
L_T (mm)	3
α_c	0.7
α_t	0.7
β_c	0.9
η_c	0.16
$í_g$	0.85
ρ_a (kg/m^3)	1.29

Table 2 gives the detail values of the design parameters of the proposed system.

To calculate electrical efficiency of any PV cell as Zondag et al. (2002) designed a theory is given by,

$$\eta_{ca} = \eta_{ref} [1 - \Phi_{ref} [T_c - T_a)] \quad (1)$$

Quantities η_{ref}, T_a and φ_{ref} are usually references to what the researcher has to set accordingly.

$$E_{out} = \eta_{ca} * I(t) * bL * n_{pv} \quad (2)$$

Equivalent thermal energy of electrical is given by

$$E_{eth} = \frac{E_{out}}{C_f} \quad (3)$$

Adding thermal gain of the proposed systems to equivalent thermal energy of electrical energy overall thermal energy of proposed system can be calculated as,

$$Q_{hourly} = \frac{E_{out}}{C_f} + Q_u \quad (4)$$

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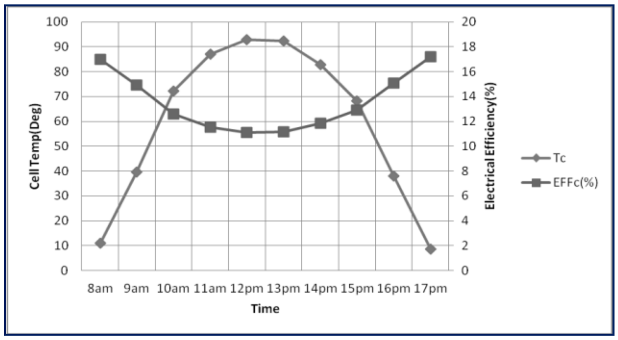

Figure 2. Comparison between cell temperature and electrical efficiency w.r.t time

The overall thermal energy of the proposed system can be derived by

$$Q_{daily} = \sum_{j=1}^{n} \frac{(\eta_{ca})_j * [I(t)]_j * bL * \eta_{pv}}{C_f} + \sum_{j=1}^{n} (Q_u)_j \tag{5}$$

Overall thermal efficiency can be derived as,

$$\eta_{TH} = \frac{\sum_{j=1}^{n} \frac{(\eta_{ca})_j * [I(t)]_j * bL * \eta_{pv}}{C_f} + \sum_{j=1}^{n} (Q_u)_j}{\sum_{j=1}^{n} [I(t)]_j * bL * \eta_{pv}} \tag{6}$$

$$Thermal\ Exergy = Q_u \left(1 - \frac{T_a}{T_{airout}}\right) \tag{7}$$

$$Net\ Exergy\ Gain = E_{out} + Q_u \left(1 - \frac{T_a}{T_{airout}}\right) \tag{8}$$

Energy balance equation of the proposed model is given by:

$$\begin{bmatrix} Rate\ of\ heat \\ received\ by \\ solar\ cell \end{bmatrix} + \begin{bmatrix} Rate\ of\ heat \\ received\ by \\ non\ packing\ area \end{bmatrix} = \begin{bmatrix} Rate\ of\ heat\ loss \\ from\ PV\ module\ to \\ air\ as\ the\ top\ loss \end{bmatrix} + \begin{bmatrix} Rate\ of\ heat\ loss\ from \\ pv\ module\ to \\ back\ surface/tedlar \end{bmatrix} + \begin{bmatrix} rate\ of\ Electricity \\ produced \end{bmatrix}.$$

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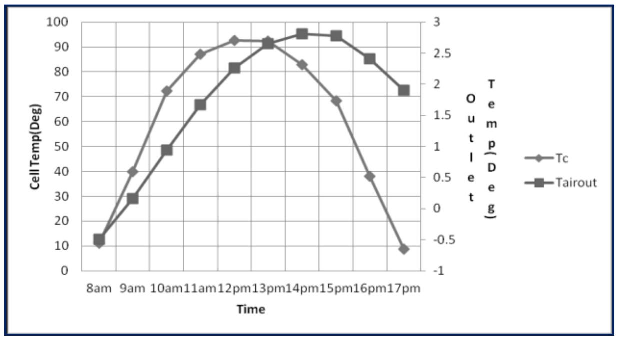

Figure 3. Comparative study of temperature between cell and duct outlet

$$\tau_g[\alpha_c\,\beta_c + (1-\beta_c)\,\alpha_T\,]I(t)bdx = [U_T(T_c - T_a) + h_T\,(T_c - T_{bs})]bdx + \eta_{ca}I(t)bdx \quad (9)$$

Simplifying

$$T_c = \frac{h_T\,T_{bs} + U_T T_a + I(t)\,(\alpha\tau)_{eff}}{U_T + h_T} \quad (10)$$

For *tedlar* of proposed model, Energy balance can be derived as,

$$\begin{bmatrix} Rate\ of\ heat\ gain\ from \\ PV\ module\ to\ tedlar \end{bmatrix} = \begin{bmatrix} Rate\ of\ heat\ loss\ from\ tedlar\ to \\ air\ side\ in\ the\ duct \end{bmatrix}.$$

$$h_T\ (T_c - T_{bs})bdx = h_{air}(T_{bs} - T_{air})bdx \quad (11)$$

Substituting Tc in Eq. (11)

$$T_{bs} = \frac{h_{air}T_{air} + U_{tT}T_a + h_{\rho 1}\ I(t)(\alpha\tau)_{eff}}{U_{tT} + h_{air}} \quad (12)$$

Energy balance of air flowing in the duct of the BIPVT system is given by,

$$\begin{bmatrix} Rate\ of\ heat\ received\ from\ tedlar \\ to\ air\ side\ in\ the\ duct \end{bmatrix} = \begin{bmatrix} Rate\ of\ heat\ gain\ by\ air \\ flowing\ in\ duct \end{bmatrix} +$$

$$\begin{bmatrix} Rate\ of\ heat\ loss\ from\ air \\ through\ insulation \end{bmatrix}$$

$$h_{air}(T_{bs} - T_{air})bdx = M_{air}C_{air}(\frac{dT_{air}}{dx})dx + U_{bb}(T_{air} - T_{ar})bdx \quad (13)$$

On substituting T_{bs} from Eqn (12) to Eqn (13) we have

$$h_{air}\left[\frac{h_{\rho 1}\ h_{\ \rho 2}I(t)(\alpha\tau)_{eff} - U_{tT}(T_{air} - T_c)}{U_{tT}\ h_{air}}\right]bdx = M_{air}C_{air}(\frac{dT_{air}}{dx})dx + U_{bb}(T_{air} - T_{ar})bdx \quad (14)$$

By $T_{air}=T_{ar}$, $T_{air}=T_{airout}$.

The temperature at the output of duct for length L can be derived as,

$$T_{airout} = \left[\frac{U_{bb}T_{ar}+U_{tair}T_a + h_{\rho 1}\, h_{\rho 2} I(t)(\alpha\tau)_{eff}}{U_{ti}}\right]\left(1 - e^{-\frac{bU_{ti}L}{M_{air}C_{air}}}\right) + T_{ar} e^{-\frac{bU_{ti}L}{M_{air}C_{air}}} \quad (15)$$

$$T_{air} = \left[\frac{U_{bb}T_{ar}+U_{tair}T_a + h_{\rho 1}\, h_{\rho 2} I(t)(\alpha\tau)_{eff}}{U_{ti}}\right]\left(1 - \frac{1-e^{-\frac{bU_{ti}L}{M_{air}C_{air}}}}{(\frac{bU_{ti}L}{M_{air}C_{air}}}\right) + T_{ar}\,\frac{1-e^{-\frac{bU_{ti}L}{M_{air}C_{air}}}}{\frac{bU_{ti}L}{M_{air}C_{air}}} \quad (16)$$

For η_{pv} row of the system the overall thermal energy can be derived as,

$$Q_u = n_{pv} * M_{air}C_{air}(T_{airout} - T_{ar}) \quad (17)$$

For heating of space of the building the energy balance equation can be derived as,

$$n_{pv} * M_{air}C_{air}\left[\frac{U_{bb}T_r+U_{tair}T_a + h_{\rho 1}\, h_{\rho 2} I(t)(\alpha\tau)_{eff}}{U_{ti}} - T_{ar}\right] * \left(1 - e^{-\frac{bU_{ti}L}{M_{air}C_{air}}}\right) + U_{bb}(T_{air} + T_{ar})A_{roof} = M_r C_{air}\left(\frac{dT_r}{dt}\right) + (UA)_t(T_{ar} - T_a) + 0.33 N_o V (T_{ar} - T_a) \quad (18)$$

Table 3. Variation of temperature at different places

Tc	**Tair(duct)**	**Tairout (duct outlet)**	**T_{ar}(room)**
11.0321	-0.5437	-0.4915	-0.5959
39.742	-0.0194	0.1598	-0.1986
72.298	0.6211	0.9442	0.298
87.1728	1.281	1.6682	0.8939
92.7663	1.8499	2.2598	1.4401
92.2978	2.2433	2.6493	1.8374
82.8908	2.448	2.8109	2.0857
68.2848	2.4816	2.7782	2.185
38.0957	2.2473	2.4089	2.0857
8.664	1.868	1.8986	1.8374

Table 4. Variation of efficiency w.r.t temp

Time	**Tc (degree) Cell temp**	**Electrical Efficiency (%)**
8am	11.0321	17.0057
9am	39.742	14.9386
10am	72.298	12.5945
11am	87.1728	11.5236
12pm	92.7663	11.1208
13pm	92.2978	11.1546
14pm	82.8908	11.8319
15pm	68.2848	12.8835
16pm	38.0957	15.0571
17pm	8.664	17.1764

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Temperature of air inside the room can be derived as

$$T_{ar} = \frac{f(t)}{a}\left(1 - e^{-at}\right) + T_{ri}\, e^{-at} \tag{19}$$

$$f(t) = \frac{1}{M_r C_{air}}\left[\{(UA)_t 0.33 N_o V\} T_a + \left\{\eta_{pv} M_{air} C_{air}\left[\frac{U_{tair} T_a + h_{\rho1}\, h_{\rho2} I(t)(\alpha\tau)_{eff}}{U_{ti}}\right]\left(1 - e^{\frac{-bU_{ti}L}{M_{air}C_{air}}}\right)\right\} + U_{bb}\left\{\frac{U_{tair} T_a + h_{\rho1}\, h_{\rho2} I(t)(\alpha\tau)_{eff}}{U_{ti}}\right\}\left(1 - \frac{1 - e^{\frac{-bU_{ti}L}{M_{air}C_{air}}}}{\frac{bU_{ti}L}{M_{air}C_{air}}}\right) A_{roof}\right] \tag{20}$$

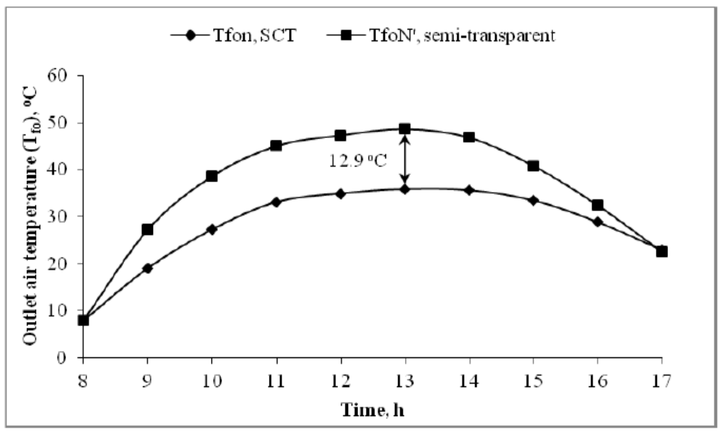

Figure 4. Variations of room air temperature w.r.t time

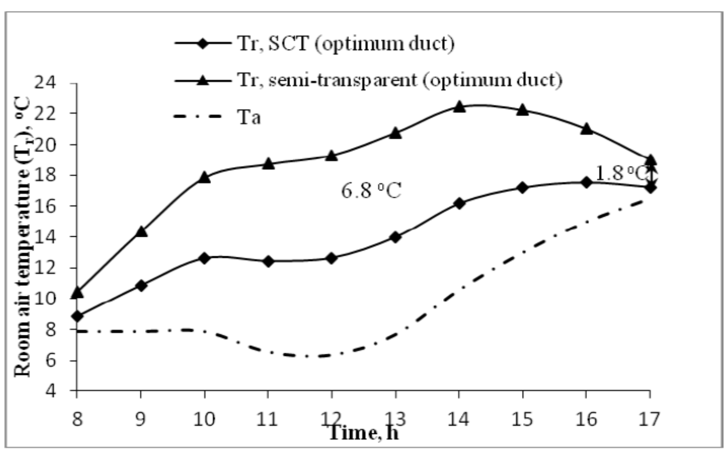

Figure 5. Variation of thermal energy w.r.t number of air changes

Figure 5 describes the variation of thermal energy w.r.t. number of air changes.

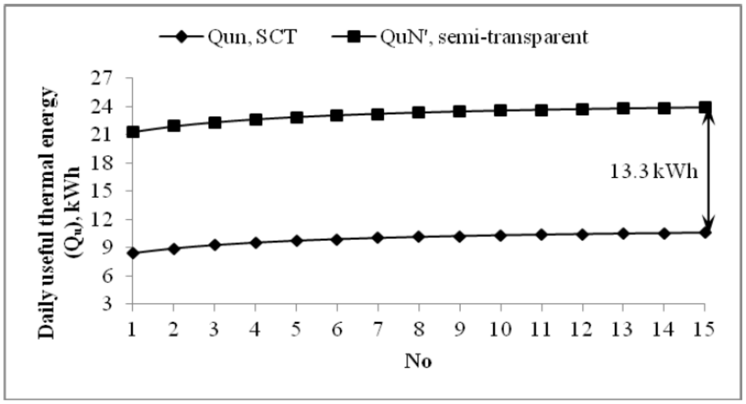

Figure 6. Variation of thermal energy w.r.t number of air changes

In case of semi-transparent PVT roof, the maximum room air temperature and maximum daily useful heat gain for a typical day of January is higher by 6.8° C. The efficiency, exergy, thermal and electrical gain have been calculated from temperature at different places from Table 3 and Table 4 after changing the parameters related to the system. The values have been compared with the previous one and percentage change is calculated with the use of "MATLAB-13". The air is blown at a pace of 1.5kg/sec inside the duct to get maximum efficiency.

3. Results and Discussion

- Figure 2 shows that even if the cell temp dies out at 5pm there is presence of duct temperature which indicates the efficiency of the module.
- A comparison has been made between electrical efficiency and exergy efficiency which shows that after combining the electrical and thermal energy the net electrical efficiency increases from 17.1% to 18.4% which can be shown from Figure 3.
- At 12.9% more outlet temperature of semi-transparent PVT it has an edge as compared to other system, which can be shown from Figure 4.
- At 13.3 kWh, semi-transparent system has more daily useful heat gain as compared to SCT roof, which can be seen from Figure 6.
- The Figure 7 shows the overall thermal electrical gain in KWH.
- Figure 8 gives better idea that present system is best suited for Srinagar climatic condition as compared to Delhi.

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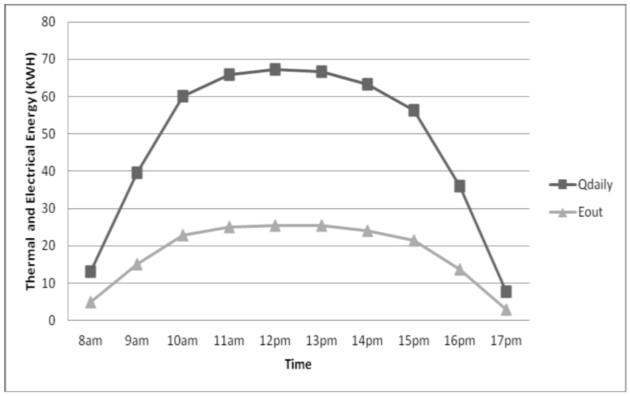

Figure 7: Variation of Electrical and Energy efficiency with Time

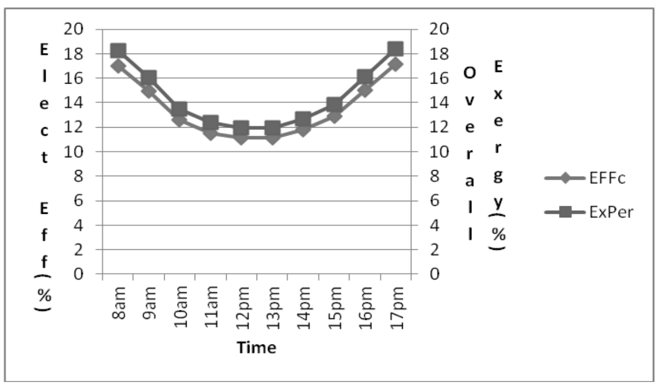

Figure 8. Variation of Electrical and Exergy Efficiency w.r.t time

4. Conclusion

Data shows that the solar intensity is maximum in Srinagar at 1pm in the month of January. If for the same system a comparison is made then it has been concluded that Srinagar gives better result as compared to Delhi, that is, almost 2% more efficient. Comparison has also been made to know about the room temperature, duct and the outlet in Table 3 and Table 4.

The present system produces almost 67KWh thermal energy per day as compared to 51KWh of previous system (Figure 7). As far as total electrical energy is concerned it produces 25 KWh per day from 8 to 5pm as compared to 23KWh of previous system. As far as efficiency is concerned this system produces 17.1% of electrical efficiency and overall exergy of 18.4% as compared to 16% and 17% of previous system.

Appendix

$(\alpha\tau)_{eff} = \tau_g[\alpha_c\,\beta_c + (1-\ \beta_c)\,\alpha_T\,]\text{-}\ \eta_c$, $U_T = \left(\frac{\mathrm{Lg}}{\mathrm{Kg}} + \frac{1}{\mathrm{ho}}\right)^{-1}$, $h_T = \left(\frac{L_T}{K_T}\right)^{-1}$, $h_{\rho 1} = \frac{h_T}{U_{T+h_T}}$,

$U_{tT} = \frac{U_T * h_T}{U_{T+h_T}} = \left(\frac{1}{h_T} + \frac{1}{U_T}\right)^{-1}$, $U_{bb} = \left(\frac{1}{h_{air}} + \frac{\mathrm{Li}}{K_i} + \frac{1}{h_r}\right)^{-1}$, $h_{\rho 2} = \frac{h_{air}}{U_{tT+h_{air}}}$, $U_{tair} = \left(\frac{1}{h_{air}} + \frac{1}{U_{tT}}\right)^{-1}$,

$U_L = (U_{bb} + U_{tair})$, $(UA)_t = (UA)_{t\_wall} + (UA)_{t\_win} + (UA)_{t\_dr}$, $(UA)_{t\_dr} = \frac{A_d}{\left(\frac{1}{h_o} + \frac{1}{h_r} + \frac{L_d}{K_d}\right)}$,

$(UA)_{t\_win} = \frac{A_{win}}{\left(\frac{1}{h_o} + \frac{1}{h_r} + \frac{L_{win}}{K_{win}}\right)}$, $(UA)_{t\_wall} = \frac{A_{wall}}{\left(\frac{1}{h_o} + \frac{1}{h_r} + \frac{L_{wall}}{K_{wall}}\right)}$.

Conflict of Interest
The authors confirm that there is no conflict of interest to declare for this publication as the work is original.

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