A Novel Topological Framework for Blood Group Compatibility Using Penta Graph Topological Space

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Abstract: This study applies Penta graph topology to the directed graph representing compatibility relations among the eight major blood groups $G = \{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$. Each vertex represents a blood group and a directed edge indicates transfusion compatibility determined by ABO and Rh factor interactions. The model reflects the hierarchical donation structure in which O^- acts as a universal donor and AB^+ as a universal recipient. Using neighborhood structures $N(v)$ derived from compatibility relations, lower, upper, and boundary Penta subgraphs were constructed. Initially, the topology generated satisfies $\eta\mathcal{P}(Si)$ ={G, ϕ}, with basis B = $\{G, \emptyset, \{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}\}$. To investigate the structural significance of individual blood groups, vertex deletion is performed for each blood group separately. The analysis reveals of that the removal O^- and AB^+ alters the basis of the induced Penta graph topology, whereas the removal of any other single blood group leaves the basis unchanged. These results identify O^- and AB^+ as the most structurally significant vertices in the blood group compatibility network. The study shows that Penta graph topology effectively captures structural dominance, resilience, and boundary behavior within biological compatibility networks.

Keywords: Blood Group Chart, Penta graph topological space.

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1.Introduction and Preliminaries

Classification of blood is a system of classifying human blood into different categories based on the presence or absence of certain antigens on the red blood cells. The two major blood group systems are the ABO blood group system and the Rh blood group system. The ABO blood group system is a blood typing system developed by Karl Landsteiner in 1901. The system classifies blood into four blood types: A, B, AB, and O. People who belong to blood group A have A antigens on their red blood cells. Similarly, people who belong to blood group B have B antigens on their red blood cells. People who belong to blood group AB have both A and B antigens on their red blood cells. People who belong to blood group O do not have any antigens on their red blood cells but have both anti-A and anti-B antibodies. Apart from the ABO blood groups, the Rh factor is also used to classify the blood groups. When the Rh factor is present, the blood group is referred to as positive, while the absence of the Rh factor refers to the blood group as negative. When the Rh factor is combined with the ABO blood groups, eight main blood groups are formed: O^+, O^-, A^+, A^-, B^+, B^-, AB^+, and AB^-. Among these groups, the O^- group is referred to as the universal donor of red blood cells, while the AB^+ group is referred to as the universal recipient of blood cells. Blood groups play a very crucial role in medicine, especially when dealing with blood transfusions, organ transplants, and pregnancy. Blood groups do not have a role to play when defining the personality, intelligence, or career of a person.

Definition 1.1. [3] The upper approximation of a subgraph H, denoted as $N^*(H)$, captures the subgraphs that overlap with H in some way but may not be fully contained within it. The approximations are based on the collection $R(G)$, which consists of distinct edge induced sub graphs of G. These sub graphs are derived from the edge sets of G. Formally, we define the upper approximation as:

$$N^*(H) = \{\cup H_i : H_i \in R(G)\ and\ H_i \cap H \neq \phi\}$$

This definition suggests that $N^*(H)$ includes all the edge-induced subgraphs H_i from $R(G)$, that share at least one edge with H. Intuitively, this represents the idea of a loose or larger approximation of H, where the graph can extend beyond the boundaries of H but still retains some overlap.

Definition 1.2. [3] The lower approximation of a subgraph H, denoted as $N_*(H)$, is more restrictive. It includes only those edge-induced subgraphs that are completely contained within H.

Formally, the lower approximation is defined as:

$$N_*(H) = \{\cup H_i : H_i \in R(G) and\ H_i \subseteq H\}$$

Thus, $N_*(H)$ consists of all the subgraphs in $R(G)$ that are subsets of H, meaning they fit entirely within the boundaries of H. This approximation can be thought of as the tightest or smallest approximation of H, where the graph cannot extend beyond H.

Definition 1.3. [3] The boundary region of H in G is defined as the difference between the upper and lower approximations:

$$B_N(H) = N^*(H) - N_*(H)$$

The boundary region captures the elements that are in the upper approximation but not in the lower approximation. In other words, it consists of subgraphs from $R(G)$ that partially overlap with H but are not fully contained within it. This can be seen as the border or boundary between H and the rest of the graph, highlighting areas where H is not completely represented.

Definition 1.4. [3] Consider a non-empty simple graph $G = (V, E)$ and a collection of distinct edge-induced subgraphs of G generated by the subsets of E. For any subgraph H of G define

$$\Gamma_R(H) = \{G, \phi, N^*(H), N_*(H), B_N(H)\}$$

Where $\Gamma_R(H)$ satisfies the following axioms

- The graph G (the full graph) and the empty graph ϕ belong to $\Gamma_R(H)$
- An arbitrary union of members of $\Gamma_R(H)$ is in $\Gamma_R(H)$
- A finite intersection of members of $\Gamma_R(H)$ is in $\Gamma_R(H)$

The collection $\Gamma_R(H)$is termed a $N-$graph topology on G. The pair $(G, \Gamma_R(H))$ is designated as the $N-$Graph topological space. The elements of $\Gamma_R(H)$ are referred to as $N-$open subgraphs in G, and the complement of an $N-$open subgraph is termed a N-closed subgraph of $\Gamma_R(H)$. A subgraph that is both a $N-$open subgraph and a $N-$closed subgraph is designated as a $N-$clopen subgraph.

2.Lower Penta and Upper Penta subgraph

In this section, a novel method for constructing new types of graphs based on the concepts of lower, upper, and boundary subgraphs are introduced. Subsequently, the definitions of Lower Penta Subgraphs, Upper Penta Subgraphs, and Boundary Penta Subgraphs are defined.

Definition 2.1. [3] Let $G = (V, E)$ be a non-empty graph with minimum 3 vertices and $\mathcal{N}(v)$ be the neighborhood of a vertex $v \in V(G)$. Consider D_i be any different subgraphs of G, then a lower approximations and upper approximations are defined by

$$\mathcal{P}_-(D_i) = \{v : \mathcal{N}(v) \subseteq D_i\}\ and\ \mathcal{P}^-(D_i) = \{v : \mathcal{N}(v) \cap D_i \neq \phi\}$$

Definition 2.2.[13] Let $G = (V, E)$ be a non-empty graph with minimum 3 vertices and $N(v)$ be the neighborhood of a vertex $v \in V(G)$. Consider D_i, i= 1, 2, 3, 4, 5 be five different subgraphs of G.

A lower Penta subgraph $\mathcal{P}_*(Z)$is defined as the union of $\mathcal{P}_-(D_i)$. Formally,

$$\mathcal{P}_*(Z) = \cup_{v\in V(G)}\{v : (\mathcal{N}(v) \subseteq D_1) \cup (\mathcal{N}(v) \subseteq D_2) \cup (\mathcal{N}(v) \subseteq D_3) \cup (\mathcal{N}(v) \subseteq D_4) \cup (N(v) \subseteq D_5)\}$$

An upper Penta subgraph $\mathcal{P}^*(Z)$ is defined as the intersection of $\mathcal{P}^-(D_i)$. Formally,

$$\mathcal{P}^*(Z) = \cup_{v\in V(G)}\{v : (\mathcal{N}(v) \cap D_1 \neq \phi) \cap (\mathcal{N}(v) \cap D_2 \neq \phi) \cap (\mathcal{N}(v) \cap D_3 \neq \phi) \cap (\mathcal{N}(v) \cap D_4 \neq \phi) \cap (N(v) \cap D_5 \neq \phi)\}$$

The boundary Penta subgraph is defined as $B_{\mathcal{P}}(Z) = \mathcal{P}^*(Z) - \mathcal{P}_*(Z)$

Representation of Blood Group Compatibility:

TaBLE 1. Blood Group Compatibility (Red Blood Cell Transfusion)

Donor(Blood Group)	Recipient (Blood Group)							
	O^-	**O^+**	**A^-**	**A^+**	**B^-**	**B^+**	**AB^-**	**AB^+**
O^-	✓	✓	✓	✓	✓	✓	✓	✓
O^+	✗	✓	✗	✓	✗	✓	✗	✓
A^-	✗	✗	✓	✓	✗	✗	✓	✓
A^+	✗	✗	✗	✓	✗	✗	✗	✓
B^-	✗	✗	✗	✗	✓	✓	✓	✓
B^+	✗	✗	✗	✗	✗	✓	✗	✓
AB^-	✗	✗	✗	✗	✗	✗	✓	✓
AB^+	✗	✗	✗	✗	✗	✗	✗	✓

The directed graph in Figure represents compatibility relationships among the eight major blood groups: O^+, O^-, A^+, A^-, B^+, B^-, AB^+, and AB^-. Each vertex denotes a blood group, and a directed edge from one vertex to another indicates compatibility in blood transfusion. The structure of the graph highlights hierarchical compatibility relations determined by antigen–antibody interactions. Thus, the directed edges provide a visual representation of transfusion pathways among the different blood types.

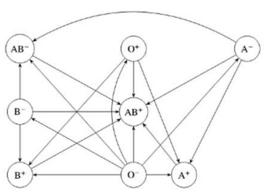

FIGURE 1. Blood Group Compatibility Graph

$N(O^+) = \{O^+, O^-, A^+, B^+, AB^+\}$

$N(O^-) = \{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$

$N(A^+) = \{O^+, O^-, A^+, A^-, AB^+\}$

$N(A^-) = \{O^-, A^+, A^-, AB^+, AB^-\}$

$N(B^+) = \{O^+, O^-, B^+, B^-, AB^+\}$

$N(B^-) = \{O^-, B^+, B^-, AB^+, AB^-\}$

$N(AB^+) = \{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$

$N(AB^-) = \{O^-, A^-, B^-, AB^+, AB^-\}$

Biological Basis of the Five Blood Group Subsets:

Category 1: Blood Groups Containing Antigen A.

$S_1 = \{A^+, A^-, AB^+, AB^-\}$

The set S_1 consists of all blood groups that possess the A antigen on the surface of red blood cells. The blood groups A^+ and A^- contain only the A antigen, whereas AB^+ and AB^- possess both A and B antigens. Therefore, all Rh-positive and Rh-negative variants containing the A antigen are included in this category.

Category 2: Blood Groups Containing Antigen B.

$S_2 = \{B^+, B^-, AB^+, AB^-\}$

This category comprises all blood groups that possess the B antigen on the surface of red blood cells. The blood groups B^+ and B^- contain only the B antigen, whereas AB^+ and AB^- possess both A and B antigens. Since the B antigen is present in each of these blood groups, they are grouped together regardless of the presence or absence of the Rh (D) antigen. Thus, S_2 represents the collection of all blood groups sharing the common biological property of the presence of the B antigen.

Category 3: Blood Groups Without A or B Antigens.

$S_3 = \{O^+, O^-\}$

This category comprises all blood groups that lack both the A and B antigens on the surface of red blood cells. The blood groups O^+ and O^- do not possess either the A or B antigen, distinguishing them from all other ABO blood groups. They differ only in the presence or absence of the Rh (D) antigen. Thus, S_3 represents the collection of blood groups characterized by the absence of both A and B antigens.

Category 4: Rh-Positive Blood Groups.

$S_4 = \{A^+, B^+, O^+, AB^+\}$

This category consists of all blood groups that possess the Rh (D) antigen on the surface of red blood cells. The presence of the Rh antigen classifies these blood groups as Rh-positive, irrespective of their ABO blood group. Thus, S_4 represents the collection of all Rh-positive blood groups.

Category 5: Rh-Negative Blood Groups.

$S_5 = \{A^-, B^-, O^-, AB^-\}$

This category comprises all blood groups that do not possess the Rh (D) antigen on the surface of red blood cells. The absence of the Rh antigen classifies these blood groups as Rh-negative, irrespective of their ABO blood group. Thus, S_5 represents the collection of all Rh-negative blood groups.

TABLE 2. Penta subgraphs $P_-(S_i)$ and $P^+(S_i)$ for blood groups

Blood Group Set	$P_-(S_i)$	$P^+(S_i)$
$\{A^+, A^-, AB^+, AB^-\}$	$\varnothing$	$\{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{B^+, B^-, AB^+, AB^-\}$	$\varnothing$	$\{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{O^+, O^-\}$	$\varnothing$	$\{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{A^+, B^+, O^+, AB^+\}$	$\varnothing$	$\{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{A^-, B^-, O^-, AB^-\}$	$\varnothing$	$\{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$

The lower Penta subgraph, upper Penta subgraph and boundary Penta subgraph are $\mathcal{P}_*(S_i) = \phi$, $\mathcal{P}^*(S_i) = \{G\}$, $B_p(S_i) = \{O^+, O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$. Then the Penta graph topology on G is given by $\eta\mathcal{P}(Si) = \{G, \emptyset\}$. A basis for this topology is $\mathscr{B} = \{G, \phi\}$

Case 1: When the blood group $\{O^+\}$ is removed:

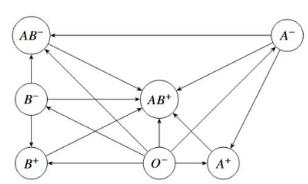

FIGURE 2. Blood Group Compatibility Graph removal of O^+

$N(O^-) = \{O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$

$N(A^+) = \{O^-, A^+, A^-, AB^+\}$

$N(A^-) = \{O^-, A^+, A^-, AB^+, AB^-\}$

$N(B^+) = \{O^-, B^+, B^-, AB^+\}$

$N(B^-) = \{O^-, B^+, B^-, AB^+, AB^-\}$

$N(AB^+) = \{O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$

$N(AB^-) = \{O^-, A^-, B^-, AB^+, AB^-\}$

Table 3. Penta subgraphs $P-(Si)$ and $P+(Si)$ for blood groups

Blood Group Set	$P_-(S_i)$	$P^+(S_i)$
$\{A^+, A^-, AB^+, AB^-\}$	$\varnothing$	$\{O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{B^+, B^-, AB^+, AB^-\}$	$\varnothing$	$\{O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{O^-\}$	$\varnothing$	$\{O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{A^+, B^+, AB^+\}$	$\varnothing$	$\{O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{A^-, B^-, O^-, AB^-\}$	$\varnothing$	$\{O^-, A^+, A^-, B^+, B^-, AB^+, AB^-\}$

Then the lower Penta subgraph, upper Penta subgraph, and boundary Penta subgraph are $\mathcal{P}_*(S_i)$={}, $\mathcal{P}^*(S_i)$ = $\{G\}$, $B_p(S_i)$ ={G}. Then the Penta graph topology on G is given by $\eta\mathcal{P}(Si)$ ={G, ϕ}. A basis for this topology is $\mathscr{B}$ =$\{G, \emptyset\}$

Case 2: When the blood group $\{O^-\}$ is removed:

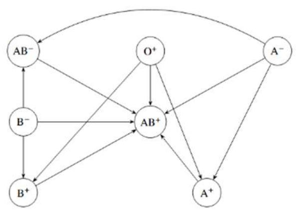

FIGURE 3. Blood Group Compatibility Graph removal of O^-

$N(O^+) = \{O^+, A^+, B^+, AB^+\}$

$N(A^+) = \{O^+, A^+, A^-, AB^+\}$

$N(A^-) = \{A^+, A^-, AB^+, AB^-\}$

$N(B^+) = \{O^+, B^+, B^-, AB^+\}$

$N(B^-) = \{B^+, B^-, AB^+, AB^-\}$

$N(AB^+) = \{O^+, A^+, A^-, B^+, B^-, AB^+, AB$

$N(AB^-) = \{A^-, B^-, AB^+, AB^-\}$

Table 4. Penta subgraphs $P-(Si)$ and $P+(Si)$ for blood groups

Blood Group Set	$P_-(S_i)$	$P^-(S_i)$
$\{A^+, A^-, AB^+, AB^-\}$	$\{A^-\}$	$\{O^+, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{B^+, B^-, AB^+, AB^-\}$	$\{B^-\}$	$\{O^+, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{O^+\}$	$\emptyset$	$\{O^+, A^+, B^+, AB^+,\}$
$\{A^+, B^+, O^+, AB^+\}$	$\{O^+\}$	$\{O^+, A^+, A^-, B^+, B^-, AB^+, AB^-\}$
$\{A^-, B^-, AB^-\}$	$\emptyset$	$\{A^+, A^-, B^+, B^-, AB^+, AB^-\}$

Then the lower Penta subgraph, upper Penta subgraph, and boundary Penta subgraph are

$\mathcal{P}_*(S_i)$={O⁺, A⁻, B⁻}, $\mathcal{P}^*(S_i)$= $\{A^+, B^+, AB^+\}$, $B_p(S_i)$=$\{A^+, B^+, AB^+\}$. Then the Penta graph

topology G is given by $\eta\mathcal{P}(Si)$={ G, ϕ, {O⁺, A⁻, B⁻},$\{A^+, B^+, AB^+\}$}. A basis of this topology

is $\mathscr{B}$ =$\{G, \{O^+, A^-, B^-\}, \{A^+, B^+, AB^+\}\}$

Case 3 : When the blood group {A⁺} is removed:
Then the lower Penta subgraph, upper Penta subgraph, and boundary Penta subgraph are $\mathcal{P}_*(S_i)$ ={}, $\mathcal{P}^*(S_i)$= $\{G\}$, $B_p(S_i)$ ={G}.Then the Penta graph topology on G is given by $\eta\mathcal{P}(Si)$ ={ G, ϕ}. A basis for this topology is $\mathscr{B}$ =$\{G,$ ϕ }

Case 4 : When the blood group {A⁻} is removed:
Then the lower Penta subgraph, upper Penta subgraph, and boundary Penta subgraph are $\mathcal{P}_*(S_i)$ ={}, $\mathcal{P}^*(S_i)$= $\{G\}$, $B_p(S_i)$ ={G}. Then the Penta graph topology on G is given by $\eta\mathcal{P}(Si)$ ={ G, ϕ}. A basis for this topology is $\mathscr{B}$ =$\{G, \emptyset\}$

Case 5 : When the blood group{B⁺} is removed:
Then the lower Penta subgraph, upper Penta subgraph, and boundary Penta subgraph are $\mathcal{P}_*(S_i)$ ={}, $\mathcal{P}^*(S_i)$= $\{G\}$, $B_p(S_i)$ ={G}.Then the Penta graph topology on G is given by $\eta\mathcal{P}(Si)$ ={ G, ϕ}. A basis for this topology is $\mathscr{B}$ ={ G, ∅}

Case 6: When the blood group$\{B^-\}$ is removed:
Then the lower Penta subgraph, upper Penta subgraph, and boundary Penta subgraph are $\mathcal{P}_*(S_i)$={}, $\mathcal{P}^*(S_i)$= $\{G\}$, $B_p(S_i)$ ={G}. Then the Penta graph topology on G is given by $\eta\mathcal{P}(Si)$ ={ G, ϕ}. A basis for this topology is $\mathscr{B}$ ={ G, ∅}

Case 7 : When the blood group{AB⁺} is removed:
Then the lower Penta subgraph, upper Penta subgraph, and boundary Penta subgraph are $\mathcal{P}_*(S_i)$ =$\{AB^-\}$,$\mathcal{P}^*(S_i)$= $\{O^+, O^-, A^-, B^-\}$, $B_p(S_i)$ ={O⁺, O^-, A^-, B^-}. Then the Penta graph topology on G is given by $\eta\mathcal{P}(Si)$ ={ G, ϕ,{AB⁻},$\{O^+, O^-, A^-, B^-\}$. A basis for this topology is $\mathscr{B}$ =$\{G, \{AB^-\}$,{O⁺, O^-, A^-, B^-} }

Case 8: When the blood group $\{AB^-\}$ is removed:
Then the lower Penta subgraph, upper Penta subgraph, and boundary Penta subgraph are $\mathcal{P}_*(S_i)$ ={}, $\mathcal{P}^*(S_i)$= $\{G\}$, $B_p(S_i)$={G}. Then the Penta graph topology on G is given by $\eta\mathcal{P}(Si)$ ={ G, ϕ}. A basis for this topology is $\mathscr{B}$ =$\{G,$ ϕ}

Case	Removal of blood group	Basis	Conclusion
1	O^+	$\mathscr{B}_{O^+} = \{G\}$	$\mathscr{B}_{O^+} = \mathscr{B}$
2	O^-	$\mathscr{B}_{O^-} = \{G, \{O^+, A^-, B^-\}, \{A^+, B^+, AB^+\}\}$	$\mathscr{B}_{O^-} \neq \mathscr{B}$
3	A^+	$\mathscr{B}_{A^+} = \{G\}$	$\mathscr{B}_{A^+} = \mathscr{B}$
4	A^-	$\mathscr{B}_{A^-} = \{G\}$	$\mathscr{B}_{A^-} = \mathscr{B}$
5	B^+	$\mathscr{B}_{B^+} = \{G\}$	$\mathscr{B}_{B^+} = \mathscr{B}$
6	B^-	$\mathscr{B}_{B^-} = \{G\}$	$\mathscr{B}_{B^-} = \mathscr{B}$
7	AB^+	$\mathscr{B}_{AB^+} = \{G, \{AB^-\}, \{O^+, O^-, A^-, B^-\}\}$	$\mathscr{B}_{AB^+} \neq \mathscr{B}$
8	AB^-	$\mathscr{B}_{AB^-} = \{G\}$	$\mathscr{B}_{AB^-} = \mathscr{B}$

TABLE 3. Basis and Conclusion after Removal of Each Blood Group

Penta Graph Topology Analysis

Results: The analysis shows that the removal of the blood groups O^- and AB + alters the basis of the blood group topological space, whereas the removal of any other single blood group does not. This mathematical result aligns with their unique biological significance: O^- is the universal red blood cell donor and AB + is the universal red blood cell recipient.

CONCLUSION

The application of Penta graph topology to the blood group compatibility digraph provides a rigorous mathematical framework for analyzing the structural properties of blood transfusion compatibility. The study demonstrates that the removal of the blood groups O^- and AB^+ alters the basis of the blood group topological space, whereas the removal of any other single blood group leaves the basis unchanged. This indicates that these two blood groups play a fundamental role in determining the underlying topological structure of the compatibility network.

The mathematical findings are consistent with their well-established biological significance. The blood group O^{-}, being the universal red blood cell donor, and AB^{+}, being the universal red blood cell recipient, occupy unique positions within the compatibility network. Their influence on the basis of the topology reflects their central role in maintaining the structural organization of the blood group system.

Therefore, Penta graph topology provides an effective mathematical tool for studying biological compatibility networks by identifying structurally significant vertices and revealing the impact of their removal on the topology of the system. This approach offers new insights into the relationship between graph topology and transfusion compatibility and can be extended to other biomedical and therapeutic network models to investigate structural stability, connectivity, and hierarchical interactions.

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