Modelling the Spread of Hospital-Acquired Infections in France: A Comparison of Patient Transfer Networks

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Project financed by Programme de Recherche Interdisciplinaire sur les Crises et la Protection Sanitaire (PRINCEPS)

Introduction
Hospital acquired infections (HAI), including emerging multi-drug resistance organisms, continue to threaten all healthcare systems. Efficient containment measures of HAIs must mobilize the entire healthcare network. Healthcare organization in France heavily relies on patient transfer to reference centres. To reduce the scale of HAI epidemic spread, modelling approaches are needed to inform decision makers on optimal regional and national infection control strategies. We explore the role of patient transfer patterns in the French healthcare network to identify contact network characteristics associated with potential epidemic spread of HAIs.

Objectives
- Reconstruct the hospital networks of HAI diagnosed patients, suspected HAI patients, and that of the entire patient population for 2012.
- Assess and compare network characteristics.
- Simulate hypothetical spread of an HAI infection in the networks.
- Simulate and assess the probability of a sustained epidemics in the networks.

Methods
Patient Discharge Summaries
- Programme de Médicalisation des Systèmes d’Information (PMSI)
- Medical, surgical, obstetric hospital (MOS)
- Postoperative and rehabilitation (SSR)

Criteria based on patients’ principal, associated, or related diagnoses
- HAI diagnosed patients network: patients with the ICD-10 code Y95
- Suspected HAI patient networks: identified diagnosed with a sensitivity of 26.3% (95% CI 13.2–42.1) and specificity of 99.5% (95% 89.8–100.0)3
- Non-specific network: encompasses all transfer patient discharge summaries

Results

Table 1. Networks Characteristics of the French Healthcare Networks

<table>
<thead>
<tr>
<th></th>
<th>HAI Network</th>
<th>Suspected-HAI Network</th>
<th>Non-Specific Patient Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>85 972</td>
<td>1 199 889</td>
<td>10 344 053</td>
</tr>
<tr>
<td>Patients</td>
<td>21 047</td>
<td>392 537</td>
<td>2 059 799</td>
</tr>
<tr>
<td>Patient Transfers</td>
<td>18 569</td>
<td>201 869</td>
<td>8 138 254</td>
</tr>
<tr>
<td>Hospitals</td>
<td>1 770</td>
<td>2 184</td>
<td>2 737</td>
</tr>
<tr>
<td>Trajectories</td>
<td>5 225</td>
<td>25 879</td>
<td>153 665</td>
</tr>
<tr>
<td>Average Path Length</td>
<td>3.75</td>
<td>3.21</td>
<td>2.40</td>
</tr>
<tr>
<td>Average Degree</td>
<td>5.90 (SD=12.5)</td>
<td>23.7 (SD=33)</td>
<td>112.27 (SD=132.46)</td>
</tr>
<tr>
<td>Average In-Degree</td>
<td>2.95 (SD=8.40)</td>
<td>11.85 (SD=20)</td>
<td>56.14 (SD=75.39)</td>
</tr>
<tr>
<td>Average Out-Degree</td>
<td>2.95 (SD=5.01)</td>
<td>11.85 (SD=19)</td>
<td>56.14 (SD=83.83)</td>
</tr>
<tr>
<td>Communities</td>
<td>20</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Average Inner Community Distance (km)</td>
<td>39.40</td>
<td>20.00</td>
<td>39.14</td>
</tr>
</tbody>
</table>

Table 2: Hospitals in each network were ranked based on their degree, authority, hub, and eigenvector centrality measures which indicate node importance. Wilcoxon Rank Sum tests were performed to compare the networks. All networks differ for each measure (p<0.05). The top 3 hospitals for each measure are shown with their department number. AP-HP: Assistance Publique - Hôpitaux de Paris; CHU: Centre HospitalierUniversitaire; CNR: Centre Hospitalier Régional

<table>
<thead>
<tr>
<th>Degree</th>
<th>Authority</th>
<th>Hub</th>
<th>Eigenvector</th>
<th>Closeness</th>
<th>Centrality</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP-HP (75)</td>
<td>CHU de Dijon (21)</td>
<td>CHU de Toulouse (31)</td>
<td>AP-HP (75)</td>
<td>CHU de Dijon (21)</td>
<td>CHU de Toulouse (31)</td>
</tr>
<tr>
<td>CLINIQUE MAUSSINS-BALET (75)</td>
<td>POLE GÉRÔTRO - RUE DES CHARMETTES (69)</td>
<td>CLINIQUE ST BRUNO FUTURE (13)</td>
<td>AP-HP (75)</td>
<td>CLINIQUE ST BRUNO FUTURE (13)</td>
<td>CLINIQUE ST BRUNO FUTURE (13)</td>
</tr>
</tbody>
</table>

Figure 1: The distribution of node degree in the three networks by the discrete power-law distribution function P(x) from Clouchet et al.’s algorithm4. A Kolmogorov–Smirnov test was used to assess the fit of a power-law distribution to each network’s degrees distribution. There is little evidence to show that a power-law distribution is not a good fit for the three networks’ degree distributions (p-values > 0.05) when assessed with optimal lower cut-offs using a goodness-of-fit based approach (at 5 degrees for the HAI-defined network, at 50 degrees for the suspected-HAI defined network, and at 426 degrees the non-specific network). However, there is evidence that the power-law is not a good fit for all networks when taking into consideration all degree values (p-values < 0.05).

Figure 2: The color map of varying hospital infection probabilities. Each hospital is subjected to 30 epidemic initiations with varying infectiousness (p) at increments of 1% (from T1=1% to T10=10%) with the hospital serving as an index case of the epidemic. We calculated the probability of hospitals sustaining an epidemic in the network for at least 50 time steps and compared the results by the hospital’s network characteristics. The probabilities are compared to the initial infected node’s degree (top left), weighted degree (top right), betweenness centrality (bottom left), and closeness centrality (bottom right). P=0 no hospital is infected; P=1 at least 1 or more hospitals are infected at the end of the 30 time steps.

Learning Points
- Movement of patients is not random in the healthcare system.
- Networks exhibit characteristics of scale-free, small-world networks.
- Directionality of movement can identify vulnerable hospitals and those more likely to act as "super-spreaders" of nosocomial infections.
- Identification of key patient reference centers (large hospitals systems, university hospitals, and regional hospitals) that most influence HAI spread.
- Regional community clustering results are consistent with previous studies that have shown that healthcare networks display a community structure.
- Expect high probability of sustained epidemic spread for hub hospitals with the highest degree, weighted degree, betweenness centrality, and closeness centrality.
- A network approach to identify vulnerable hospitals.

Conclusion
Different patient inclusion criteria could impact network characteristics. The suspected-HAI healthcare network may be more reliable in predicting potential spread of HAIs. The identification of key hospital centres, patient flow trajectories, and regional clustering may serve as a basis for novel wide-scale infection control strategies.

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