Catch-up Scheduling for Childhood Immunization

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Outline

• The catch-up scheduling problem
  • Current paradigm
  • The need for an automated tool
  • Problem description

• A Dynamic Programming (DP) algorithm

• Usage and dissemination

• Summary and ongoing work
### Problem Description: The Recommended Schedule

**Recommended Immunization Schedule for Persons Aged 0 Through 6 Years—United States • 2009**

For those who fall behind or start late, see the catch-up schedule

<table>
<thead>
<tr>
<th>Vaccine ▼</th>
<th>Age ▼</th>
<th>Birth</th>
<th>2 months</th>
<th>7 months</th>
<th>12 months</th>
<th>15 months</th>
<th>18 months</th>
<th>18-24 months</th>
<th>2-3 years</th>
<th>4-6 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hepatitis B</td>
<td>Birth</td>
<td>HepB</td>
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</tbody>
</table>

This schedule indicates the recommended ages for routine administration of currently licensed vaccines, as of December 1, 2008, for children aged 0 through 6 years. Any dose not administered at the recommended age should be administered at a subsequent visit, when indicated and feasible. Licensed combination vaccines may be used whenever any component of the combination is indicated and other components are not contraindicated and if approved by the Food and Drug Administration for that dose of the series. Providers should consult the relevant Advisory Committee on Immunization Practices statement for detailed recommendations, including high-risk conditions: http://www.cdc.gov/vaccines/pubs/acip-list.htm. Clinically significant adverse events that follow immunization should be reported to the Vaccine Adverse Event Reporting System (VAERS). Guidance about how to obtain and complete a VAERS form is available at http://www.vaers.hhs.gov or by telephone, 800-822-7967.

### Problem Description: The Catch-up Guidelines

**Catch-up Immunization Schedule for Persons Aged 4 Months Through 18 Years Who Start Late or Who Are More Than 1 Month Behind—United States • 2009**

The table below provides catch-up schedules and minimum intervals between doses for children whose vaccinations have been delayed. A vaccine series does not need to be restarted, regardless of the time that has elapsed between doses. Use the vaccine appropriate for the child’s age.

<table>
<thead>
<tr>
<th>Vaccine</th>
<th>Minimum Interval Between Doses</th>
<th>Catch-up Scheduling for Childhood immunization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hepatitis B</td>
<td>4 weeks</td>
<td>Birth</td>
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<tr>
<td>DTaP</td>
<td>6 weeks</td>
<td></td>
</tr>
<tr>
<td>Haemophilus influenzae type b</td>
<td>6 weeks</td>
<td></td>
</tr>
<tr>
<td>Pneumococcal</td>
<td>6 weeks</td>
<td></td>
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<tr>
<td>Varicella</td>
<td>12 months</td>
<td></td>
</tr>
<tr>
<td>Hepatitis A</td>
<td>12 months</td>
<td></td>
</tr>
</tbody>
</table>
Problem Description: Untimely Vaccination

Statistics from Luman et al. 2002¹:

- Only 9% of children received all recommended vaccines at the recommended ages.
- 55% of children did not receive all recommended doses by 2 years of age.
- 8% of children received at least 1 vaccination dose too early to be considered valid.

More recent statistics from NIS ² suggest only slight improvements.

² http://www.cdc.gov/vaccines/stats-surv

Problem Description: Causes of Untimely Vaccination

Reasons often cited for incorrect and untimely vaccination:

- parental negligence and misinformation
- incomplete or incorrect schedules constructed by health professionals due to:
  - insufficient knowledge and addition of new vaccines to the lineup, ³, ⁴
  - problem complexity and tedious process of manual construction.
- missed opportunities for vaccination ⁵
- environmental and socioeconomic standings.

Problem Description: The Remedy

Aim

Provide a freely available and easy to use automated tool for constructing catch-up schedules aimed at providers and caretakers.

Immediate benefits:
- Eliminate human error.
- Speedup process.
- Improve public access to vital information.

Long-term benefits:
- Alleviate missed opportunities.
- Improve timely vaccination rates.
- Improve awareness and parental participation.

The Catch-up Scheduling Problem

Paradigm

Given past vaccination history for a child, each remaining dose that can be feasibly administered and not contraindicated must be scheduled.

Feasibility requirements:
- Minimum and maximum age requirement for each dose of each vaccine.
- Gap between (not necessarily successive) doses of the same vaccine must not violate the minimum allowed. This gap may vary by vaccine, dose, current age and/or age at which previous dose is administered.
- “Live-virus” vaccines may be administered during the same visit or at least 28 days apart.
The Catch-up Scheduling Problem

Paradigm

Given past vaccination history for a child, each remaining dose that can be feasibly administered and not contraindicated must be scheduled.

Possible contraindications:

- The previous dose is administered at an age that no longer warrants further vaccination.
- The current age of the child no longer warrants further vaccination.

Example (Contraindicating PCV)

The second dose of PCV is deemed final if the first dose is administered after age 12 months or the current age is 24-59 months. In either case, the third and fourth doses are unnecessary.

Discretionary measures:

- The aggressiveness of catch-up regime, i.e.
  
  Administer when recommended
  
  Vs

  Administer as soon as feasibly possible

- The maximum number of simultaneous administrations.
- The number of doctor’s visits.
The Catch-up Scheduling Problem & Machine Scheduling

<table>
<thead>
<tr>
<th>Machine scheduling</th>
<th>Catch-up Scheduling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jobs</td>
<td>Vaccine doses</td>
</tr>
<tr>
<td>Release and due dates</td>
<td>Window for each dose</td>
</tr>
<tr>
<td>Number of processors</td>
<td>Number of simultaneous administrations</td>
</tr>
<tr>
<td>Separation time between jobs (Chain) Precedence</td>
<td>Spacing between doses</td>
</tr>
<tr>
<td></td>
<td>Doses must be given in sequence</td>
</tr>
</tbody>
</table>

**Proposition**

The catch-up scheduling problem remains NP-hard:
1. without minimum gap between doses and live vaccines,
2. without any maximum age for a dose and without live vaccines, and
3. without a limit on the number of simultaneous administrations.

The catch-up scheduling problem is polynomially solvable without live vaccines and without any limit on the number of simultaneous administrations.

**The Tool**

INPUT

Child's vaccination history.

Vaccine Modeling Language (VML).

SCHEDULER

Algorithms to construct schedule.

OUTPUT

Charts containing schedule for all remaining doses.
The Tool (User Input and Interface)

Birth Date: [Input]
Name: [Input]
Scenario: [Options]

Example (VML for PCV)

The Tool (Vaccine Modeling Language)
Parameters:

- $\tau$: time horizon
- $I$: set of vaccines
- $n(v)$: number of doses of vaccine $v \in V$
- $\tau(v, k) = \{ t \in T : \minAge(v, k) \leq t \leq \maxAge(v, k) \}$

Decision variables:

- $x_t = 1$ if a doctor's visit is scheduled on day $t$; 0 otherwise.
- $y_{v,k,t} = 1$ if the $k$th dose of vaccine $v$ is administered on day $t$; 0 otherwise.

Constraints:

C1. Administer each dose at-most once:

$$\sum_{t \in \tau(v, k)} y_{v,k,t} \leq \begin{cases} 1, & \text{if } k = 1 \\
\sum_{t \in \tau(v, k-1)} y_{v,k-1,t}, & \text{otherwise.}
\end{cases}$$
Optimization Models (Integer Programming)

Parameters:
- \( \tau \) = time horizon, \( V \) = set of vaccines, \( n(v) \) = number of doses of vaccine \( v \in V \)

\( R(v) \) = the number of rows from the second part of the VML input
- Rows: \( r = 1, \ldots, R(v) \)

Decision variables:
- \( x_t = 1 \) if a doctor’s visit is scheduled on day \( t \) and 0 otherwise.
- \( y_{v,k,t} = 1 \) if the \( k \)th dose of vaccine \( v \) is administered on day \( t \) and 0 otherwise.

Constraints:

C3. Regulating gap between doses:

\[
\sum_{t \in \tau(v,k_2(v,r),r)} t \cdot y_{v,k_2(v,r),r} - \sum_{t \in \tau(v,k_1(v,r),r)} t \cdot y_{v,k_1(v,r),r} \geq \text{minGap}(v,r).
\]

Optimization Models (Integer Programming)

Parameters:
- \( \tau \) = time horizon
- \( I \) = set of vaccines
- \( n(v) \) = number of doses of vaccine \( v \in V \)

Decision variables:
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- \( y_{v,k,t} = 1 \) if the \( k \)th dose of vaccine \( v \) is administered on day \( t \) and 0 otherwise.

Constraints:

C4. Scheduling doctor visits:

\[
|V| \cdot x_t - \sum_{v \in V} \sum_{k=1}^{n(v)} y_{v,k,t} \geq 0
\]
Parameters:
\( \tau = \) time horizon
\( V = \) set of vaccines
\( n(v) = \) number of doses of vaccine \( v \in V \)

Decision variables:
\( x_t = 1 \) if a doctor’s visit is scheduled on day \( t \) and 0 otherwise.
\( y_{v,k,t} = 1 \) if the \( k \)th dose of vaccine \( v \) is administered on day \( t \) and 0 otherwise.

Constraints:
C5. Limiting number of simultaneous administrations:
\[
\sum_{v \in V} \sum_{k=1}^{n(v)} y_{v,k,t} \leq \maxSim.
\]

Objective Function:
- Large reward for administering dose
- Penalize delay in administering dose
- Penalize deviation from recommended gap
A DP Algorithm

Day $t$
- $S_0$: Partial (initial) Schedule

Day $t + 1$
- Schedule vaccine A
- Schedule vaccine B
- Schedule vaccine A & B
- No vaccine scheduled

Day $t + 2$

Day $t + 3$

Catch-up Scheduling for Childhood immunization
A DP Algorithm

Day $t$

- $S_0$: Partial (initial) Schedule

Day $t + 1$

- $S_2$
- $S_4$

Day $t + 2$

Day $t + 3$

Schedule vaccine A
Schedule vaccine B
Schedule vaccine A & B
No vaccine scheduled

Catch-up Scheduling for Childhood immunization
A DP Algorithm

Dominance criteria

Schedule $S_X$ dominates $S_Y$ if:
1. The number of doses administered in $S_X$ is no less than $S_Y$ for each vaccine,
2. The timing of each critical dose administered in $S_Y$ is no earlier than in $S_X$, and
3. The total delay in administering doses in common is less in $S_X$.

Proposition

If $S_X$ dominates $S_Y$ then any completion of $S_Y$ cannot be better than the best completion of $S_X$ and thus, $S_Y$ is unwarranted.
A DP Algorithm

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**Catch-up Scheduling for Childhood Immunization**

27/28

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**Catch-up Scheduling for Childhood Immunization**

28/28
The Tool (Output Charts)

Scenario 1

A 4 month old child who has received 1 dose of HepB at birth and one each of DTaP, Hib and PCV at 2 months of age.

Schedule generated on Oct 27, 2007 (10/27/2007)
Birth Date: Jun 27, 2007 (06/27/2007)

Scenario 1... cont.

A 4 month old child who has received 1 dose of HepB at birth and one each of DTaP, Hib and PCV at 2 months of age.

Schedule generated on Oct 27, 2007 (10/27/2007)
Birth Date: Jun 27, 2007 (06/27/2007)
**Scenario 2**

A 1 year old child who is presumed not received any vaccination to date.

<table>
<thead>
<tr>
<th>Age (weeks)</th>
<th>CD Today</th>
<th>52</th>
<th>56</th>
<th>60</th>
<th>64</th>
<th>68</th>
<th>72</th>
<th>76</th>
<th>80</th>
<th>84</th>
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<th>96</th>
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<th>104</th>
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<th>112</th>
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</thead>
<tbody>
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</tbody>
</table>

*Dose may be administered anytime during specified interval. However, gaps to subsequent doses may not be valid when administered after first day in interval.*

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**Scenario 2... cont.**

A 1 year old child who is presumed not received any vaccination to date.

<table>
<thead>
<tr>
<th>Age (weeks)</th>
<th>CD Today</th>
<th>52</th>
<th>56</th>
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<th>64</th>
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*Dose may be administered anytime during specified interval. However, gaps to subsequent doses may not be valid when administered after first day in interval.*
Usage and Dissemination

Catch-up Scheduling for Childhood Immunization

Summary and Ongoing Work

• Prototype ✓
• Handover to CDC/AAP for piloting and validation ✓
• Disseminate through www … ✓

36,000+ downloads since June 08

• Guide rule makers in stating rules for new vaccines ✓
• Combination vaccines
• Adolescent and adult vaccination
• Schedules for immunosuppressed children (children with diabetes, HIV, undergoing therapy, etc.)
• Extend to other countries 🇺🇸 🇹🇷