Research and Applications

LabRS: A Rosetta stone for retrospective standardization of clinical laboratory test results

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ABSTRACT

Objective: Clinical laboratories in the United States do not have an explicit result standard to report the 7 billion laboratory tests results they produce each year. The absence of standardized test results creates inefficiencies and ambiguities for secondary data users. We developed and tested a tool to standardize the results of laboratory tests in a large, multicenter clinical data warehouse.

Methods: Laboratory records, each of which consisted of a laboratory result and a test identifier, from 27 diverse facilities were captured from 2000 through 2015. Each record underwent a standardization process to convert the original result into a format amenable to secondary data analysis. The standardization process included the correction of typos, normalization of categorical results, separation of inequalities from numbers, and conversion of numbers represented by words (eg, “million”) to numerals. Quality control included expert review.

Results: We obtained 1.266×10^9 laboratory records and standardized 1.252×10^9 records (98.9%). Of the unique unstandardized records (78.887×10^3), most appeared <5 times (96%, eg, typos), did not have a test identifier (47%), or belonged to an esoteric test with <100 results (2%). Overall, these 3 reasons accounted for nearly all unstandardized results (98%).

Conclusion: Current results suggest that the tool is both scalable and generalizable among diverse clinical laboratories. Based on observed trends, the tool will require ongoing maintenance to stay current with new tests and result formats. Future work to develop and implement an explicit standard for test results would reduce the need to retrospectively standardize test results.

Key words: LOINC, clinical laboratory information systems, controlled vocabulary

OBJECTIVE

Clinical laboratories in the United States do not have an explicit result standard to report the 7 billion laboratory tests results they produce each year. The absence of a result standard creates inefficiencies and ambiguities for secondary data users. We developed and tested a tool to standardize the results of laboratory tests in a large, multicenter clinical data warehouse.

BACKGROUND AND SIGNIFICANCE

The contribution of the clinical laboratory to medical practice is widely recognized. US health care providers order 7 billion laboratory tests annually to aid in the prevention, diagnosis, and management of disease.¹ Research and operational improvement projects such as clinical trials and utilization reviews also frequently rely on laboratory results.² In order to maintain accreditation and receive

reimbursement for their services, clinical laboratories must comply with strict regulatory requirements, which often entail continuous quality control, proficiency testing, and laboratory inspections to ensure high-quality test performance.³

Despite the federally mandated scrutiny of clinical laboratories, details of the data they produce remain largely unstandardized. Laboratories have the freedom to select the test names displayed on their menus and the reference ranges for normal and abnormal results.⁴ Laboratories can also choose the format of their results and associated units. For example, a positive result can have multiple synonyms: positive, confirmed, detected, immunized, or screen positive. Likewise, positive units for white blood cell counts have at least 23 documented variations.⁵ While the lack of laboratory data standardization may not hinder the daily activities of most health care providers, unstandardized data creates inefficiencies and ambiguities for secondary data users.^{5–7}

Although no standard currently focuses on the format of laboratory results, standards do cover other aspects of laboratory data. Logical Observation Identifiers Names and Codes (LOINC) and Systemized Nomenclature of Medicine – Clinical Terms provide identifiers for laboratory tests.^{8–10} For example, LOINC provides a code to designate a test result to describe the color of urine, but does not specify a standard color palette to constrain the possible results.¹¹ Similarly, multiple formats, rather than a single uniform format, exist to denote a cancelled test.¹² Health Level-7 focuses on data transfer formats rather than explicit formats for each laboratory test. If such standards did exist, their adoption and enforcement by clinical laboratories, which routinely produce billions of laboratory results per year, would represent a major accomplishment.

To overcome the current limitations in laboratory data standardization, we developed a tool to standardize historical laboratory results for secondary data users.

MATERIALS AND METHODS

The Veterans Health Administration's (VA) Corporate Data Warehouse (CDW) of laboratory results has accumulated a variety of synonymous inputs over the 16 years it has been accumulating data. We sought to develop a process to consolidate these disparate formats, syntaxes, regional dialects, and locally acquired habits of laboratory test result communication into a structured vocabulary that reflects the clinical significance of the original result format, a process we refer to as standardization. Our standardization algorithm dissects a laboratory result into its components, classifies each component, and translates the component to a limited set of clearly defined terms. We provide quality control of the standardization process with expert review of each standardized result and provide summary statistics to assess overall performance.

The author (RGH) programmed the algorithm in Visual Studio with C# and Structured Query Language commands. The program ran on a 64-bit Windows 7 operating system with an Intel Xeon CPU E31270 at 3.40 GHz and 8 gigabytes of random access memory. Interested readers can find the algorithm in a public repository.¹³

Standardization process

Our automated process to standardize laboratory results can be separated into 3 main steps: extraction, transformation, and loading. The extraction step pulls the laboratory result data from the CDW. The transformation step converts the raw data into a standardized format. The load step moves the standardized data into a new location in

the database. Quality control is performed at the completion of the load step.

Extraction

We selected data from 27 VA facilities in the northeastern United States, which encompasses major metropolitan areas such as Boston, New York, Philadelphia, Pittsburgh, and Baltimore, along with more rural locations. The data span the years 2000–15.

The data elements extracted from the CDW database consisted of a laboratory test identifier and the laboratory test result. The laboratory test identifiers are represented by LOINC codes. These codes spanned all sections of the laboratory, including chemistry, hematology, microbiology, blood bank, virology, molecular, and reference testing. The coverage of blood bank tests is not complete, because some VA facilities store blood bank results in a separate system (Vista Blood Establishment Computer System). Similar to its commercial equivalents, the CDW has separate storage for results longer than approximately 250 characters, such as interpretations of blood smears, serum and urine protein electrophoresis, and microbiology cultures. We did not attempt to standardize these interpretive results. We also did not standardize the CDW fields designated for units, reference ranges, and specimen type. The study used no personally identifiable information, and therefore was exempt from Institutional Review Board review.

Transformation

The transformation of the inputs from the CDW database into a consistent format involved 2 steps. The first step parsed the result into components. The most common result components included inequalities and numbers. As an example, the parser would separate a result such as "<5" into "<" and "5." The second step standardized the components. In our previous example, had the inequality originally been placed on the right side ("5>"), the standardization step would flip the inequality, because we standardized inequalities to read from left to right. In this way, the combination of the parse and standardize steps can create a single result format from 2 different result inputs, "<5" and "5>."

The complexity of the transformation step extended beyond inequality placement. It identified and standardized results that might include units (eg, "1 mg/dl"), typos, numbers represented by words, numeric transformations (eg, log scales), scientific notation, etc. Units within the result should be reported in the "Units" column, a separate column from the results column. Results frequently involve a combination of components placed in various orders, such as "<1.30 million copies/ml." The parse step would separate this result into 4 components: "<," "1.30," "million," and "copies/ml." These components would be standardized into 3 components: an inequality "<," a number "1 300 000" and a unit "copies/ml." For this study, we used the Unified Code for Units of Measure as a standardized system for units.¹⁴

Not all results have a meaningful interpretation. For example, a typo can make a result uninterpretable, while an acronym can be ambiguous. An example of an ambiguous acronym is the result "ND," which refers to "not done" in some laboratories and "not detected" in others. We wanted our standardization process to apply outside of the VA, so we avoided any standardization that required knowledge about site-specific nomenclature, such as interpretation of acronyms like "ND." If the standardization process recognized the result as ambiguous or uninterpretable, it would report the result as "Non-standard." For results that did not fit a recognized pattern, a flag exists to indicate the result could not be mapped.

Table 1. Standardized laboratory result schema

Name	Description	DataType
TestId	Original LOINC code	varchar(50)
Result	Original result	varchar(254)
TestScale	Original scale type of LOINC code	varchar(254)
MappedYN	Was the standardization process successful?	varchar(1)
MapFunc	The name of the function that standardized the result	varchar(50)
Inequality	If present, the inequality	varchar(2)
Number	If numeric, the number	varchar(100)
AfterDecimal	If numeric, the number of digits after the decimal	integer
Field1	A placeholder for non-numeric information	varchar(100)
Field2	A placeholder for non-numeric information	varchar(100)
General	The reason a result did not receive a detailed map	varchar(30)
Pretty	The format of the result for use in reports	varchar(100)

Software engineers will recognize the transformation step as an abstract factory design pattern. The base class contains a function to map the result, while each derived class contains a specific implementation of the map function. When the base class receives the laboratory result and test identifier, it determines which derived class to use. The derived class then performs its map function on the inputs. Each map function in the derived class parses and maps the result.

Load

A specially designed table holds the output of the result standardization process (Table 1). It includes the input to the program, the test identifier and unstandardized result, and the output of the program, a set of columns that contain the standardized result as well as quality control. The first output column, “MappedYN,” indicates whether the process recognized the result with a “Y” (yes) or “N” (no). Results recognized by the standardization process, even ambiguous (eg, “ND”) and uninterpretable (eg, “.”) results, will contain a Y. In contrast, results not recognized by the standardization process will have a value of N, which commonly occurs for novel typographical errors (eg, “abc123”). The next column, “MapFunc,” details how the program recognized the result. The third through fifth columns contain information about the standardization of numbers, including the presence of an inequality and the number of digits after the decimal. The sixth and seventh columns contain the type of categorical result and the standardized categorical result. As an example, a blood type of “A+” would read “ABO” as the type of categorical result and “A positive” as the standardized result for blood type (see Supplementary Table 2 for a complete list). If a result contains a unit, which typically occurs for numeric (noncategorical) results, these columns also hold the unit. The eighth column, “General,” can apply to any result, including numeric and categorical tests. It contains “Non-standard” for results without a clear interpretation and “Not performed” for cancelled tests.

Data types are relative to Microsoft SQL Server 2012. For an example of table output, see Supplementary Table 3.

When complete, the output table allows users of the database to convert an unstandardized laboratory result into a standardized result. The test identifier and unstandardized result allow this table to link back to the original data.

Metrics/quality control

Summary statistics

To measure the progress of our standardization effort, we monitored the proportion of standardized results to total results. A test frequently

has many of the same results in the database. We removed duplicate results for the same test to track the proportion of standardized non-duplicate results to the total nonduplicate results. This metric provided a more realistic estimate of our progress, because it takes roughly the same amount of effort to standardize a result with no duplicates as it does to standardize a result with many duplicates.

To investigate the cause of unstandardized results, we established 3 metrics, A–C. Metric A calculates the number of unstandardized results with <5 occurrences in the entire database. Metric B represents the proportion of unstandardized laboratory results that belonged to a LOINC code with <100 total results. Metric C accounts for unstandardized results without a LOINC code. A single result could influence multiple metrics. For example, a result could occur only twice (metric A) and belong to a LOINC code with 25 total results (metric B).

Expert review

Two board-certified clinical pathologists independently reviewed the output of the standardization process until they reached agreement. They compared each unstandardized laboratory result to the standardized version. If the standardized version omitted critical details or overinterpreted the result, a modification to correct the issue in the standardization process was initiated. The iterative process of review and modification continued until both experts concluded that no standardized results misrepresented the original data.

In addition to manual review of the individual laboratory results, we also performed a semiautomated review to assess the internal consistency of the data (Supplementary Table 2). As a simple quality control check, we compared the total number of rows before and after the standardization process. If the number of rows differed, the standardization process had added or deleted data rows in error. As a more complex quality control check, we reviewed results that appeared incompatible with the assigned LOINC code. For example, a LOINC code for an HIV viral load expects a quantitative result, and therefore we labeled for manual review the nonquantitative result “positive.” Each quality control metric received expert review.

Maintenance

Maintenance refers to the ongoing effort required to keep our standardization process current as new laboratory results and tests enter the database. To approximate the maintenance cost, we recorded the first occurrence of each new test and result over the lifespan of the database. We counted unique results on a per-test basis, meaning a result of “45” received a separate count for each test that reported

Table 2. The laboratory result standardization process

Total results	1 266 349 351	(%)
Total results standardized ^a	1 252 109 700	98.9
Total results not standardized	14 239 651	1.1
A: Result appears <5 times ^b	13 230 159	1.0
B: LOINC code with <100 results ^b	4130	0.0
C: Missing LOINC code	1 651 448	0.1
Not A, B, or C	762 336	0.1
Total distinct results	2 682 196	(%)
Total distinct results standardized ^c	2 603 309	97.1
Total distinct results not standardized	78 887	2.9
A: Result appears <5 times ^b	75 385	2.8
B: LOINC code with <100 results ^b	1476	0.1
C: Missing LOINC code	36 958	1.4
Not A, B, or C	1622	0.1

^aConcept token coverage; ^brelative to the total results; ^cconcept type coverage.

this value. High numbers of new tests and results in the years closest to the present suggest a need for ongoing maintenance.

RESULTS

From the selected 27 facilities in the CDW database, we obtained 1.266×10^9 records, each of which consisted of a laboratory result and a corresponding test identifier (Table 2). After removing duplicates, 2.682×10^6 records remained (0.21%). Our standardization process created 2.603×10^6 standardized records, which covered 98.9% ($1.252 \times 10^9 / 1.266 \times 10^9$) of the total records and 97.1% ($2.603 \times 10^6 / 2.682 \times 10^6$) of the nonduplicate records. Table 3 contains abbreviated examples of standardized test results, while Supplementary Table 3 contains the complete examples.

Standardization process

Unstandardized

We dedicated significant effort to determine why records could not be standardized. The majority of the unstandardized records appeared <5 times in the database. These rare records represented 96% of the unstandardized records after removing duplicates ($75.385 \times 10^3 / 78.887 \times 10^3$) and 93% of the total unstandardized records ($13.230 \times 10^6 / 14.240 \times 10^6$). Other explanations for an unstandardized record included the absence of a test identifier (47%, $36.958 \times 10^3 / 78.887 \times 10^3$ unique records; 12%, $1.651 \times 10^6 / 14.240 \times 10^6$ total records) and an esoteric test with <100 results (2%, $1.476 \times 10^3 / 78.887 \times 10^3$ unique records; <1%, $4.130 \times 10^3 / 14.240 \times 10^6$ total records). Overall, at least 1 of these reasons occurred in nearly all of the unstandardized results (98%, $77.265 \times 10^3 / 78.887 \times 10^3$ unique records; 95%, $13.477 \times 10^6 / 14.240 \times 10^6$ total records). See Table 2, metrics A–C.

Multiple factors contributed to the existence of records with <5 occurrences, a notable anomaly in a database with such a large number of results: typographical variants, free-text responses, and “database errors.” Typographical variants with unambiguous interpretations did undergo standardization, like these example variants for positive: “poditive,” “popsitive,” “posiive,” “posirive,” and “positibe.” Ambiguous typographical variants did not receive standardization: “po” could indicate “pos,” a variant of “positive” or “PO,” an abbreviation meaning “by mouth”; the ambiguous variant

Table 3. Examples of standardized results

Map Function	Original Result	Standardized Result
General	TNP	Not performed
	QNS	Not performed
	Comment	Nonstandard result
	Canc	Not performed
Quantitative	3%	3, %
	<=12	<=, 12
	932.87	932.87
Quantitative, log10	1.8 LOG10	63, Log10: 1.8
Quantitative, units	>10 000 COPIES/ML	>, 10 000, (copies)/mL
	<0.3 U/L	<, 0.3, U/L
Quantitative, IgE antibody	<.35 KU/L (%ASM:93)	<, 0.35, 93
	>100 KU/L(%ASM:3466)	>, 100, 3466
	>.35 KU/L, %ASM:15	>, 0.35, 15
Ordinal	POS	Positive
	Detected	Positive
	POSITIVE	Positive
	POSITIVE	Positive
Nominal	DK YELLOW	Dark yellow
	LTBRN	Light brown
Hepatitis C genotype	Type 1	1
	1, NO SUBTYPE	1
	HCV 1	1
	TYPE 1 Unable to subtype	1
ABO Rh	O POSITIVE	O Positive
	O POSITIVE	O Positive

The standardized result column contains only the most relevant information from the actual output as a comma-separated list. Supplementary Table 3 contains the full table as described by the schema in Table 1. The “Original Result” column in the “ABO Rh” group contains the number zero instead of the letter “O.” TNP = test not performed; QNS = quantity not sufficient.

“poc” could indicate “pos,” a variant of “positive” or “POC,” an abbreviation for “point of care.” Free text, such as that describing a blood smear interpretation, generally could be found in the test comment section, but occasionally existed as a result input. The descriptive nature of free text makes these entries unique, and since the database truncates results at 250 characters, they were frequently uninterpretable. “Database errors” refers to differences in the representation of the test results in the database compared to the results when viewed by the health care provider. For example, a test for platelet estimate can read “M” in the database but expand to “Marked Decrease” when viewed by the health care provider. This error category is unique to the VA database and beyond our ability to correct. In our experience, the unstandardized records contained much less useful information than the standardized records.

Difficult to standardize

Although we were able to standardize the results for the overwhelming majority of records, some results required significant effort to resolve. The challenges in developing our standardization process most often involved tests that had multiple result formats, tests with categorical results without an established list of categories, and the use of abbreviations and acronyms.

Most tests had multiple result formats. As an example, the test for hepatitis C genotype had 12 different formats, including “Hepatitis C genotype 1 detected,” “Hepatitis C genotype 1,” “Genotype 1,” “Type 1,” and “1.” Results that identified multiple genotypes created even more result formats: “Type 1 and type 2,”

“type 1/type 2,” and “type 1, type 2.” Each result format requires modification of the standardization process to correctly interpret.

Most categorical tests did not share an established list of result categories. For example, a test that records the color of urine contained many variants on the color yellow, including “clear yellow,” “pale yellow,” “straw yellow,” “light yellow,” etc. With the inclusion of spelling variants, this test had nearly 1400 unique interpretable results.

Many tests use difficult-to-decipher abbreviations: “QNS” (quantity not sufficient), “TNP” (test not performed), “ND” (not done or not detected), “TNTC” (too numerous to count), “TMTC” (too many to count), etc. On first pass, these abbreviations often seem like typographical errors, and it was sometimes a challenge to distinguish true abbreviations from entry errors.

Quality control

The quality control metrics listed in Supplementary Table 2 helped to improve the result standardization process. For example, one metric identified ~6% of unique laboratory results containing a discrepancy between the result expected from the LOINC code and the actual result (Supplementary Table 2, Result1.LOINCScale). One facility had reported its tests for vitamin D in a format typical of a test for allergens, “<.35 kU/l; %ASM:8,” because allergen tests frequently employ “<.35 kU/l” as the lower limit of detection, and the acronym “ASM” represents an allergen scoring schema known as the alternate scoring method.¹⁵ As another example of the importance of the quality control metrics, we identified “Laboratory studies,” a LOINC code (26436-6) without an obvious clinical interpretation.

Maintenance

To estimate the effort required to maintain this dataset with up-to-date laboratory standards, we tracked the first occurrence of each unique laboratory result and LOINC code in the database over the last 16 years. As shown in Figure 1, previously unobserved laboratory results and LOINC codes continued to appear in high quantities even in the 16th year. The last 5 years alone contain the first occurrence of 670 000 laboratory results, or ~25% of the database’s total unique results. This pattern suggests that a process that standardizes laboratory results in the CDW will necessitate frequent updates to stay current.

Figure 1. A cumulative distribution function of the first appearance of each unique LOINC code (dashed line) and laboratory result (solid line) in the last 16 years. An identical laboratory result for 2 LOINC codes received 2 counts. The increase in laboratory tests after 2005 coincides with the adoption of a new version of LOINC (v2.14).

DISCUSSION

This work demonstrates the development and feasibility of using a tool for large-scale laboratory result standardization. In a dataset with over 1 billion laboratory results, nearly 99% of all results were successfully standardized. The results originated from multiple facilities in a large geographic area, equivalent to one-quarter of the United States, and spanned 16 years, a long time period for an American health care database. The contributing facilities ranged from large, urban academic affiliates, such as the Harvard-affiliated VA Medical Center in West Roxbury, Massachusetts, to small, rural facilities, such as the 67-operating-bed VA Medical Center in Togus, Maine. We standardized all tests, unlike repositories built to study a specific patient population, which tend to narrow their focus to specific tests, tests performed on specific patients, or both. Our standardization process relies on an automated and therefore reproducible method. We also manually reviewed each output to ensure high accuracy as part of the quality control.

Much work remains on the topic of laboratory result standardization. Despite our standardization efforts, approximately 15 million laboratory results (1% of the total) either lacked a standardized value or had a standardized value without a clear interpretation. At best, each of these results reflects a patient-provided specimen and an added financial cost without a clear benefit. At worst, they represent a potential source of medical error. Even with identical results, the interpretation can still vary between labs. For example, 2 labs can both report the result of 3+ with different ordinal scales such that the highest value on one scale, 3+, differs from 4+, the highest value on the other.

Specific areas of laboratory result standardization in need of attention include developing a standard for laboratory results, acceptance of the standard by clinical laboratories, and developing pragmatic solutions to ease its implementation.

Many laboratory tests do not have a standardized result format. The absence of a standard leads clinical laboratories to define their own result formats, which often differ between laboratories. Regenstrief, the developer of LOINC test identifiers, has invested some effort into initiating a result standard.¹⁶ At the current time, the medical literature contains few, if any, practical implementations of the incomplete result standard proposed by LOINC. Manufacturers of test kits and equipment also have the potential to influence a result standard. They could clearly list the expected results within the technical specifications of their tests. The subset of tests with interpretive, also called “free text,” responses like a peripheral blood smear represent the most difficult test results to standardize.

The widespread adoption of a laboratory result standard would involve a dialog between the producers of laboratory results (eg, clinical laboratories, reference laboratories), payers (eg, Centers for Medicare and Medicaid Services, private insurance companies), and regulators (eg, College of American Pathologists, Centers for Disease Control and Prevention, US Food and Drug Administration), which all have influence over the results of laboratory tests. In the United States, clinical laboratories must adhere to the Clinical Laboratory Improvement Amendments, a regulatory standard that governs their operations.³ Organizations like the College of American Pathologists and the Joint Commission have a large influence on the enforcement of the Clinical Laboratory Improvement Amendments, which could sway the adoption of a result standard. Other avenues to implementation could include standardized laboratory data to calculate value-based purchasing metrics or to gain an economic advantage through better analytics.

With or without a widely adopted laboratory result standard, input validation would greatly reduce the number of typographical errors, such as those we observed. Such errors required us to deduce the intent of the individuals who entered those results. A better solution would be to require individuals who enter results to specify their interpretation in a predefined format.

We considered the generalizability of our approach to result standardization to non-VA patient populations and different electronic health records. For instance, the VA lacks representation by certain medical specialties, specifically pediatrics and obstetrics, and tests performed exclusively within these specialties would not have appeared in our study. As an impromptu evaluation, we applied our methods to 10 million laboratory results from a tertiary-care center with a different electronic health record vendor. The standardization process performed closer to 100%, likely because it did not have the “database errors” unique to the VA. Modifying the program was necessary to account for idiosyncratic laboratory result formats unique to this facility, and further study is needed to confirm these initial findings.

Improved methods to standardize laboratory results like ours could benefit users of the CDW and other clinical data repositories. At the current time, users of the CDW provide quality-of-care metrics, benchmark utilization, predict future costs of care, track the outbreaks of infection, prepare for natural disasters, and produce original research. Each user must perform laboratory result standardization, which leads to duplicate efforts, loss of time, and, in our experience, variable quality. Currently, one group of users of the CDW, the Veterans Aging Cohort Study,¹⁷ has validated and adopted our methods for specific tests. Further adoption of laboratory result standardization throughout the database would reduce the burden on individual users, thus improving the quality and timeliness of their work. Interested users can find the tool in a public repository.¹³

CONCLUSION

We developed a tool to standardize laboratory result formats for secondary data use. In a test of its capabilities, we standardized a dataset of 1.3 billion test results produced by VA laboratories in 27 facilities over 16 years. The tool standardized 98.9% of laboratory results, and multiple experts agreed with the standardized results it produced. The ability of the tool to standardize such a high proportion of a large dataset from laboratories that do not have system-wide regulations for the format of test results suggests that the tool is both scalable and generalizable among diverse laboratory testing environments. The continued influx of new tests and test results will require ongoing maintenance of the tool to stay current. Future work to develop and implement an explicit standard for test results would reduce the need to retrospectively standardize test results.

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COMPETING INTERESTS

The authors have no competing interests to declare.

CONTRIBUTORS

RGH designed and developed the process, standard, and results analysis software; analyzed data; and drafted and revised the paper. DBQ analyzed data and drafted and revised the paper. AR drafted and revised the paper.

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SUPPLEMENTARY MATERIAL

Supplementary material is available at *Journal of the American Medical Informatics Association* online.

REFERENCES

1. Lundberg G. Adding outcome as the 10th step in the brain-to-brain laboratory test loop. *Am J Clin Pathol*. 2014;141(6):767–69.
2. Hauser R, Shirts B. Do we now know what inappropriate laboratory utilization is? An expanded systematic review of laboratory clinical audits. *Am J Clin Pathol*. 2014;141(6):774–83.
3. Centers for Disease Control and Prevention. *Clinical Laboratory Improvement Amendments (CLIA): CLIA Laws and Regulations*. <http://www.cdc.gov/clia/regulatory/default.aspx>. Accessed September 22, 2016.
4. Gillespie RS, Johnson LC. One size does not fit all: interpreting laboratory data in pediatric patients. *AMIA Annu Symp Proc*. 2003;850.
5. McDonald C. Issues in the Standardization of Clinical Laboratory Results. *CLIA C*. 2013;1–44 Powerpoint.
6. Dixon BE, McGowan JJ, Grannis SJ. Electronic laboratory data quality and the value of a health information exchange to support public health reporting processes. *AMIA Annu Symp Proc*. 2011;322–30.
7. Raebel MA, Haynes K, Woodworth TS, et al. Electronic clinical laboratory test results data tables: lessons from Mini-Sentinel. *Pharmacoepidemiol Drug Safety*. 2014;23(6):609–18.
8. Forrey AW, McDonald CJ, DeMoor G, et al. Logical observation identifier names and codes (LOINC) database: a public use set of codes and names for electronic reporting of clinical laboratory test results. *Clin Chem*. 1996;42(1):81–90.
9. Benson T. The history of the Read Codes: the inaugural James Read Memorial Lecture 2011. *Inform Primary Care*. 2011;19(3):173–82.
10. IHTSDO. *SNOMED CT: The Global Language of Healthcare*. <http://www.ihtsdo.org/snomed-ct/>. Accessed September 22, 2016.
11. LOINC. *Color of Urine*. <http://s.details.loinc.org/LOINC/5778-6.html?sections=Simple>. Accessed September 22, 2016.
12. Darcy TP, Barasch SP, Souers RJ, et al. Test cancellation: a College of American Pathologists Q-Probes Study. *Arch Pathol Lab Med*. 2016;140(2):125–29.
13. Hauser R. *Laboratory Test Result Standardization*. <https://github.com/hau serg/LaboratoryTestResultStandardization>. Accessed December 18, 2016.
14. Schadow G, McDonald CJ. *The Unified Code for Units of Measure*. Regenstrief Institute and UCUM Organization: Indianapolis, IN; 2009.
15. Valcour A. *Allergy Testing for the 21st Century*. https://www.labcorp.com/wps/wcm/connect/4e6bbc804a162d8599a5fd90b80e7bfff/Allergy_Article_for_Web.pdf?MOD=AJPERES. Accessed September 22, 2016.
16. McDonald C, Huff S, Deckard J, et al. *Logical Observation Identifiers Names and Codes (LOINC®) Users' Guide*. 2016. Preface Page 2 (June, 2016). <http://loinc.org/downloads/files/LOINCManual.pdf>. Accessed September 19, 2016.
17. Justice AC, Dombrowski E, Conigliaro J, et al. Veterans Aging Cohort Study (VACS): Overview and description. *Med Care*. 2006;44(8 Suppl 2):S13–24.