



Database tool

Revenant: a database of resurrected proteins

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Abstract

Revenant is a database of resurrected proteins coming from extinct organisms. Currently, it contains a manually curated collection of 84 resurrected proteins derived from bibliographic data. Each protein is extensively annotated, including structural, biochemical and biophysical information. Revenant contains a browse capability designed as a timeline from where the different proteins can be accessed. The oldest Revenant entries are between 4200 and 3500 million years ago, while the younger entries are between 8.8 and 6.3 million years ago. These proteins have been resurrected using computational tools called ancestral sequence reconstruction techniques combined with wet-laboratory synthesis and expression. Resurrected proteins are commonly used, with a noticeable increase during the past years, to explore and test different evolutionary hypotheses such as protein stability, to explore the origin of new functions, to get biochemical insights into past metabolisms and to explore specificity and promiscuous behaviour of ancient proteins.

Database URL: <http://revenant.inf.pucp.edu.pe/>

Introduction

As a time machine, a combination of *in silico* and wet laboratory approaches allow the prediction of most probable sequences of proteins coming from organisms that lived millions of years ago (1). These predicted and synthesized sequences coming from extinct organisms are called resurrected proteins. Protein resurrection consists

mainly in five steps (Figure 1) (2, 3). In the first one, a set of extant sequences, homologous to the ancestral protein to be studied, are aligned and used to estimate a phylogenetic tree. Phylogenetic trees are used to infer evolutionary relationships between ancestral and extant organisms. In a tree, extant organisms are represented by the terminal nodes or tips of the tree, (Figure 1), while

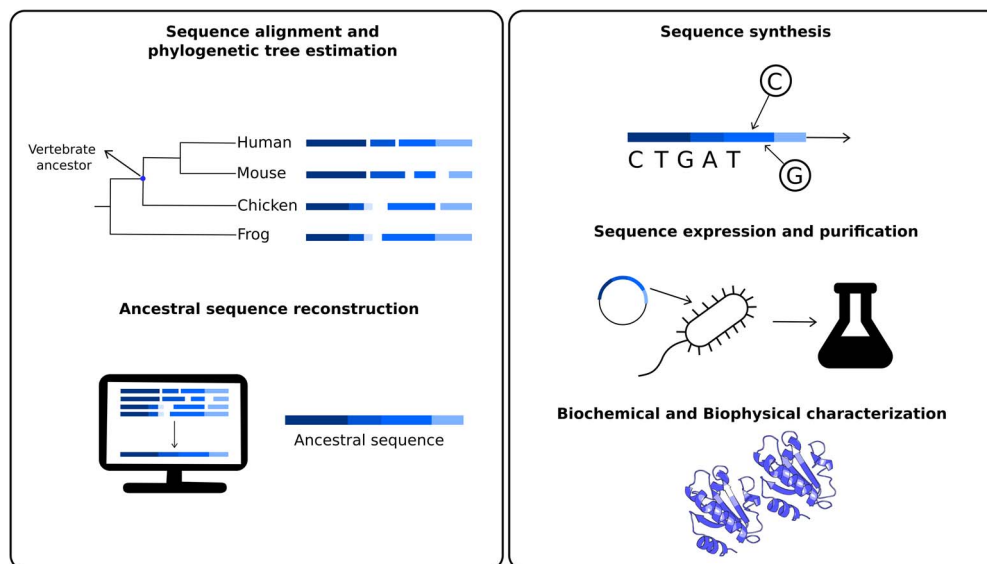


Figure 1. Schematic representation of the different steps to obtain resurrected proteins. The first step involves sequence similarity searches of a given protein to obtain a set of homologous sequences, involving the ancestral nodes to be studied. For example, one could be interested in studying biochemical properties of the studied protein in the last common ancestor for all vertebrates. Using these sequences, it is possible to estimate a phylogenetic tree to define the ancestral node to be reconstructed. In the second step, ancestral sequence reconstruction techniques are applied to estimate most probable sequences in the studied node. The third step involves the ancestral sequence synthesis. This sequence is then inserted into a vector, cloned, expressed and purified (fourth step). The fifth and final step involves a series of biochemical and biophysical characterization.

the ancestral organisms are represented by internal nodes. As an example, Figure 1 indicated the node representing the extinct organism corresponding to the last common ancestor from all extant vertebrates, or at least for those present in the set of homologous sequences considered. Using these evolutionary relationships, in the second step, it is possible to infer the most probable sequence for each of the ancestral states using the so called ancestral sequence reconstruction (ASR) techniques. These methods comprise a set of computational tools using different algorithms such as maximum parsimony (4), maximum likelihood (5–7) as well as Bayesian methods (8). In the third step, the predicted ancestral sequences could be synthesized using molecular biology techniques. If the ancestral reconstruction involves recent ancestors, site-directed mutagenesis using an extant gene can be used to obtain the ancestral sequence (9). However, in those cases where remote proteins are resurrected, gene synthesis (10) or gene fragments assembly are required to obtain the ancestral gene. Once synthesized, the gene is cloned, expressed and purified (fourth step). Then, the protein could be further experimentally characterized and studied as any other present day protein (fifth step). Most of these experiments consist in different biochemical and biophysical characterizations and also structural determination using X-ray crystallography or nuclear magnetic resonance.

The reliability of protein resurrection relies on the inference protocol used. Ambiguous estimation, dependence on

tree topologies, approximations in evolutionary models and the difficulty to model indels are among the most common problems detected in resurrection (1, 2, 11–13). However, better results are obtained considering and minimizing those caveats. Furthermore, the creation of experimentally based phylogenies has contributed with a controlled system for ASR algorithms benchmarking (14).

Besides their caveats, ASR and protein resurrection are powerful strategies for testing different biological hypotheses. For example, phenotypic adaptations in dim-vision in vertebrates were recently elucidated using ancestral reconstruction and biochemical experimentation (15). Dim-vision in vertebrates is mediated with a family of proteins called rhodopsins. Slight variations in rhodopsin sequences during evolution confer the molecular basis of the spectral tuning observed in different organisms adapted to their environments (16). The authors found that 15 replacements (~3% of the average length of the rhodopsins) are essential to understand the functional adaptation. Moreover, some of these replacements occurred multiple times in vertebrate evolution strongly suggesting the existence of positive selection. Using positive selection analysis over a set of homologous proteins is a commonly used procedure to detect important positions associated with functional adaptations (17). However, this evolutionary pattern was not detected using rhodopsins evolutionary analysis, showing the importance of the use of ASR and biochemical characterization to unveil the evolution of

Revenant
resurrected protein database

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Browse

Click on the Revenant identifier to access any of the resurrected proteins:

List View
Timeline View

Entry	Structures
RV7: 3-isopropylmalate dehydrogenase (IPMDH) Description: The ancestral IPMDH sequence belonging to the LCA of <i>Bacillus</i> sp. Estimated chronological time: 950 Mya	 3U1H
RV8: Fish Galectins Congenerin (Gal) Description: The ancestral Con sequence belonging to the LCA of Congenerin I (ConI) and Congenerin II (ConII) Estimated chronological time: N/A	 3AJZ 3AK0
RV9: Thioredoxin (Trx) Description: The ancestral Trx sequence belonging to the LCA of Bacteria Estimated chronological time: 4.2–3.5 Gya	 4BA7
RV10: Thioredoxin (Trx) Description: The ancestral Trx sequence belonging to the LCA of Archaea Estimated chronological time: 4.2–3.5 Gya	 2YNX
RV11: Thioredoxin (Trx) Description: The ancestral Trx sequence belonging to the LCA of Archaea and Eukarya Estimated chronological time: 4.2–3.5 Gya	 3ZIV

4




4 Gya: Origin of life

[\[Credits\]](#)

4.2–3.5

4.2–3.5 Gya

RV9: Thioredoxin (Trx)
The ancestral Trx sequence belonging to the LCA of Bacteria

RV10: Thioredoxin (Trx)
The ancestral Trx sequence belonging to the LCA of Archaea

RV11: Thioredoxin (Trx)
The ancestral Trx sequence belonging to the LCA of Archaea and Eukarya

3.5

3.5 Gya

RV30: Imidazole glycerol phosphate synthase (ImGP-S); cyclase subunit HisF
The ancestral HisF sequence belonging to the Last Universal Common Ancestor (LUCA)

RV79: Imidazole glycerol phosphate synthase (ImGP-S); cyclase subunit HisF
The ancestral HisF sequence belonging to the Last Universal Common Ancestor (LUCA)

3.5




3.5 Gya: LUCA

[\[Credits\]](#)

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Figure 2. Two different browsing capabilities are available in Revenant. In the first one (top panel) proteins are listed sequentially using their RV codes. In the second browser (bottom panel) we display the Revenant proteins in an Earth's timeline showing important biological events since the origin of life.

Revenant
resurrected protein database

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What's new?

- 4/10/2019: ~10 new resurrected proteins added.
- 6/28/2018: ~30 new resurrected proteins added.
- 6/11/2018: Revenant Beta 1 released.
- 6/10/2018: New chains added for RV23: β -lactamase Class A.

Have Questions?

Please visit our Frequently Asked Questions section: [FAQ](#)

For inquiries or more, please visit our contact info section: [Contact](#)

Citing Revenant:

Revenant: a database of characterized resurrected proteins.
Matias Carletti, Alexander Morzon, Emilio Garcia-Rios, Layla Hirsch, Silvana Fornasari and Gustavo Parisi

Integrated Resources:

Revenant uses the following external resources:

[PDB](#) [UniProt](#) [Gene Ontology](#)

Welcome to Revenant

Revenant contains a hand-curated collection of 84 resurrected proteins where 46 of them have at least one crystallographic structures. It summarizes a total of 78 crystalized structures of resurrected proteins. All entries in Revenant have been annotated with different information such as: the ancestral node used in the reconstruction, methodologies used for sequence estimation, used sequence alignments, ligand characterization, etc. Several resurrected proteins have additionally, biochemical parameters (i. e. Km, kcat) and thermodynamics parameters characterizing their stability. The oldest Revenant entry corresponds to a reconstruction from ~4200 millions years (MY) and the younger to just ~7.55 MY. All the Revenant proteins are extensively linked with other databases such as PDB, UniProt, Gene Ontology, PubMed and NCBI.

Search for protein name, Revenant ID or PDB ID:

Search...

Example entries:
Green Fluorescent Protein (RV1) | Aminergic toxin (Tx) (RV37) | Uricase (UR) (RV27)

chalcone isomerases
RV80: Chalcone Isomerases (CHI) (SWKR)
The ancestral CHI sequence belonging to the LCA of Chalcone Isomerases and Chalcone Isomerases - Like proteins
RV81: Chalcone Isomerases (CHI) (SWL7)
The ancestral CHI sequence belonging to the LCA of Chalcone Isomerases

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Figure 3. Screenshot of Revenant web server showing the home page and search utilities.

dim-vision in vertebrates. In a similar way, the used of ASR and resurrection techniques has had a key role to address different biological questions, such as specificity and biological activity (18), stability (19), promiscuity (20), study of alternative evolutionary histories (21), epistasis (22), evolutionary analysis of visual pigments (23), rational engineering (24) and emergence of new active sites (25), influence of evolutionary trajectories (26) and effect of duplication in functional divergence (27) just to mention a few of a large list of examples. Interestingly, as phylogenies could be calibrated with fossil records, resurrected proteins could recreate most probable states of proteins spanning very different geological times. The most challenging resurrections are about the very beginning of life on Earth (~4000 millions of years (28)).

In this work we present Revenant, the first database of resurrected proteins. It contains a manually curated collection of resurrected proteins which have been biochemically, biophysically and/or structurally characterized. Revenant proteins span several millions of years. The oldest entry corresponds to a reconstruction age between 4200 and 3500 million years ago which corresponds to the thioredoxin protein (28) (RV9, RV10 and RV11) and the younger entries between 8.8 and 6.3 million years ago corresponding to uricase (29) (RV74). Revenant proteins could display unique ancestral features. As the explained above example with the rhodopsins, experimental assays on resurrected proteins could reveal their structural arrangements, conformational diversity and dynamisms, differential stability and ligand binding affinities. These piece of evidence, along with the

use of molecular phylogenies, could represent extremely useful information to test hypotheses about the origin of promiscuity, conformational epistasis, structural divergence and functional diversification grounded on a large-scale analysis. Also, the availability of a curated database as Revenant could offer a resource for evaluating the impact of evolutionary trajectories (22) on broadly used bioinformatic methods as homology modelling (30) as well as to test mechanistic evolutionary models of proteins (31, 32).

Database fields and contents

Each resurrected protein in Revenant represents the most probable sequence in a given node for a given phylogenetic analysis. Likewise, Revenant contains 84 entries (i.e. RV1-RV84) where 45 of them have at least one known crystallographic structure. Considering different structures of the same protein, Revenant contains a total of 78 crystalized structures of resurrected proteins. Using bibliographic information and manual curation, all entries have been annotated with different information such as the ancestral node used in the reconstruction, its estimated age, ASR methodologies used for sequence estimation, sequences and softwares used for the multiple alignments and phylogenetic estimation, structure availability and their ligand characterization and primary citation. Additionally, several entries have biochemical (i. e. Km, kcat) and biophysical parameters (i.e. melting temperature, Δ Gunfolding). Furthermore, all the Revenant proteins are extensively linked with other databases such as PDB (33), UniProt (34), Gene Ontology (35) and PubMed.

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RV7: 3-isopropylmalate dehydrogenase (IPMDH)

The ancestral IPMDH sequence belonging to the LCA of *Bacillus* sp.
Estimated Chronological Time: 950 Mya

ANCESTRAL SEQUENCE RECONSTRUCTION (ASR):

Protein family sequences: LeuB protein sequences (IPMDH)

MSA amount of sequences: 21

Sequence database: GenBank

MSA Software: ClustalV2 and then refined manually using Geneious v.5.0.3.

Phylogeny Software: N/A

Phylogeny Method: Maximum Likelihood (ML)

Phylogeny Evolutionary model: LG+I+G

ASR Software: MrBayes version 3.1.2
ASR Method: Bayesian
ASR Substitution model: GTR

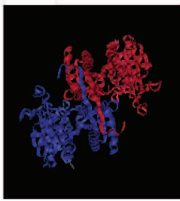
300 Sequence name: ANC4

```

1 MKKKI AVLPG DGIGPEVMEA AIEVLKAVAE RFGHEFEFEY GLIGGAAIDE AGTPLPEETL DVCKGSDAIL LGAVGGPKWD ONPSELPEK GLLGIRKGLD
101 LFNLRPVKV YDSLADASPL KKEVIEGVDL VIVRELTGG YFGEPSERYE EGEEAAVDTL LYTREEIERI IRKAFELALT RKKKVTSDK ANVLESSRLM
201 REVAEEVAKE YPDVELEHML VDNAAAMOLIR NPROFDIVIV ENFNGDILSD EASMITGSLG MLPSASLSLD GLGLYEPVNG SAPDIAGIKY ANPLATLISA
301 AMMLRHSGFL EEEKAIEKA VEKVLAEGYR TADIAKPGGK YVSTTEHTD VKAAVDELA TSAIMTAYV
                    
```

STRUCTURES OF THE RESURRECTED PROTEINS: 1

3U1H



3U1H PDB

Crystal structure of IPMDH from the last common ancestor of *Bacillus*

Exp. Method: X-RAY DIFFRACTION

Classification: OXIDOREDUCTASE

Resolution: 2.8

Taxonomy ID: 1409

Source: *Bacillus* sp. (in: Bacteria)

Chains for 3U1H: 2

A

B

Chain Length: 390

Molecular weight: 42593.3

Biological process: GO:0009098 GO:0055114

Cellular component: GO:0005737

Molecular Function: GO:0000287 GO:0003862 GO:0016616 GO:0051287

```

1 HHHHHHDYDI PTTENLYFQG AMKKKI AVLPG DGIGPEVME AIEVLKAVA ERFGHEFEFE YGLIGGAAID EAGTPLPEET LDVCKGSDAI
91 LLGAVGGPKWD ONPSELPEK KGLLGRKGL DLFANLRPVK VYDSLADASP LKKEVIEGVD LVIVRELTGG LYFGEPSERYE EGEEAAVDTL
181 LLYTREEIERI IIRKAFELALT TRKKKVTSDK KANVLESSRL WREVAEEVAKE EYPDVELEHML VDNAAAMOLIR NPROFDIVIV ENFNGDILSD
271 DEASMITGSLG MLPSASLSLD DGLGLYEPVNG SAPDIAGIKY IANPLATLISA AMMLRHSGFL EEEKAIEKA VEKVLAEGYR RTADIAKPGGK
361 KYVSTTEHTD EVKAAVDELA TSAIMTAYV
                    
```

Ligands for chain A: 0

Chain	ID	Formula	Ligand name
No ligands found for chain A.			

PROTEIN BIOCHEMICAL PARAMETERS:

Substrate	Kcat (s-1)	Kcat/KM (s-1 mM-1)	KM (mM)
IPM	362.2±294.2	214.3±18.5	1.69±15.9
NAD	N/A	N/A	0.97±22.4

Kcat (s-1): Catalytic Constant - Kcat/KM (s-1 mM-1): Catalytic Efficiency - KM (mM): Michaelis-Menten Constant

PROTEIN THERMODYNAMIC PARAMETERS:

pH	Tm (°C)	Topt (°C)	Teq (°C)	ΔG _{unf} (KJ/mol)
N/A	65.3	70 ± 68	75.1	110.8 ± 92.8

Tm (°C): Melting Temperature - Topt (°C): Optimum Temperature - Teq (°C): Equilibrium Temperature - ΔG_{unf} (KJ/mol): Gibbs' free energy of unfolding

PRIMARY CITATION:

On the origin and evolution of thermophily
Author(s): Hobbs, J.K.; Shepherd, C.; Saul, D.J.; Demetras, N.J.; Haaning, S.; Monk, C.R.; Daniel, R.M.; Arcus, V.L.
Journal: Molecular Biology and Evolution 2011. **Page(s):** 825-835. **DOI:** 10.1093/molbev/mrs253
PubMed ID: 21998276 | **PubMed Central ID:**





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Figure 4. Main entry page. Each entry starts with a title followed by a brief explanation of the biological relevance of the resurrected protein. Additionally, each entry has fields regarding ancestral sequence reconstruction, information about their structures, biochemical and biophysical parameters and, finally, the primary citation.

Database access and user interface

Resurrected proteins in Revenant can be easily found searching by protein family name and/or PDB code. The browser contains two modes for protein search, one displays all Revenant entries as a list and the other shows a geological timeline indicating the approximate age of each Revenant entry (Figure 2).

Using the search or browse capabilities it is possible to access all Revenant entries. They are displayed along with a short description about the resurrected protein and, when it is available, the approximate age of the ancestral node (Figure 3). Further information is displayed in four different sections (Figure 4) for each entry: ‘ancestral sequence reconstruction’ contains all the information related to the ASR approach used for a given reconstruction. It also shows the reconstructed sequence and its name. The ‘structures of the resurrected proteins’ section summarizes the information about available structures, ligands, chains and biological function. The third section contains information about protein biochemical parameters like k_{cat} and affinity constants (such as K_M) for given ligands as well as thermodynamic parameters (such as T_{opt} , T_m , and $\Delta G_{unfolding}$). Actually, ~23% of the entries in Revenant contain physicochemical information. The fourth and last section shows information about primary citation where the protein was resurrected. Revenant website also contains Frequently Asked Questions (FAQ) and tutorial sections to allow non-expert users to easily explore the database.

Implementation

Revenant database was designed with microservices architecture. Two main elements of the system are the presentation and data components. The presentation elements exchange data using a RESTful API and the JavaScript Object Notation. The Java programming language and Spring framework leverage the data component implementation. MySQL is used for data storage and the ReactJS framework is used for presentation. Revenant offers users both graphical web interface access and RESTful web services from <http://revenant.inf.pucp.edu.pe/>.

Conclusions

Revenant database offers a well-curated, updated and annotated collection of resurrected proteins. We think that Revenant can be used to explore the fascinating world of the increasing examples of resurrected proteins and their use to illuminate interesting biological and evolutionary questions (36). Furthermore, our database of ancient proteins could also be a source of sequence, structure, conformational diversity and biochemical data

to test further biological hypothesis and to develop new tools related with structural bioinformatics, 3D protein modelling and protein evolution.

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Conflict of interest. None declared.

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