Computational Modelling of the Haemodynamics in Coiled and Uncoiled Cerebral Aneurysms

Hasha Dar

***Abstract*— This assignment investigates the use of computational fluid dynamics (CFD) to analyse the haemodynamics of cerebral aneurysyms when treated via endovascular coil emboilsation. I utilise a simplfied model of a basilar bifurcated artery with a saccular aneurysm for this assignment. The area where coils are inserted are modelled as a porous medium and my results show a positive change in the haemodynamics of the artery. Specifically, the flow of blood and pressure is reduced to negligible in the saccular region of the aneurysm and the flow through the bifurcartion is much improved. The results show that coil emboilisation can be an effective treatment for a cerebral aneurysm - preventing it from growing or rupturing. This assignment simplifies the problem as to place emphasis on the "CFD workflow," and to emulate the experience of an industrial engineer or researcher using CFD for a project.**

***Index Terms*— Cerebral aneurysms, endovascular coil embolisation, computational haemodynamics**

I. Introduction

Cerebral aneurysms are formed due to the detoriation of the normal arterial structure leading to a dilation or bulge in the vessel wall, typically called a sac. The development of a saccular cerebral aneurysm (accounting for 90% of cases) occurs in approximately 3% to 5% of the general population - the majority of which are asymptomatic [1], [2]. However, there is a risk of rupture of the aneurysm in approximately 2% to 6% of cases leading to significant intercranial bleeding [3]. In most cases, the diagnosis is a subarachnoid hemmorage (SAH), with mostly fatal or life-altering prognoses: between 25% to 50% of SAH are fatal, with another 50% resulting in disability [4].

II. Methods

III. Results and Discussion

IV. Conclusion

Acknowledgment

The ESI Group (Paris, France), developers of the CFD-ACE+ multiphysics software platform, are kindly acknowledged for allowing the use of the software for this assignment.

V. Introduction

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H. Dar is a fourth year undergraduate student on the MEng Mechanical Engineering Programme at University College London, London, WC1E 6BT (e-mail: hasha.dar.19@ucl.ac.uk).

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VI. Guidelines for Manuscript Preparation

Do not change the template font sizes or line spacing to squeeze more text into a limited number of pages. The preferred font is 10-pt Times New Roman. Use italics for emphasis; do not underline words.

Place your figures in the text as you expect them to appear in print. Further instructions on figure usage appear in Section VI. Although IEEE will do the final formatting of your paper, we expect you to approximate the final form appearance for all versions submitted to TMI via ScholarOne®to the extent possible.

A. Abbreviations and Acronyms

Define abbreviations and acronyms the first time they are used in the text, even after they have already been defined in the abstract. Abbreviations such as IEEE, SI, ac, and dc do not have to be defined. Abbreviations that incorporate periods should not have spaces: write "C.N.R.S.," not "C. N. R. S." Do not use abbreviations in the title unless they are unavoidable (for example, "IEEE" in the title of this article).

B. Other Recommendations

Use one space after periods and colons. Hyphenate complex modifiers: "zero-field-cooled magnetization." Avoid dangling participles, such as, "Using (1), the potential was calculated." It is not clear who or what used (1). Write instead, "The potential was calculated by using (1)," or "Using (1), we calculated the potential."

Use a zero before decimal points: "0.25," not ".25." Use "cm^3," not "cc." Indicate sample dimensions as "0.1 cm $\times$ 0.2 cm," not "0.1 $\times$ 0.2 cm^2." The abbreviation for "seconds" is "s," not "sec." Use "Wb/m^2" or "webers per square meter," not "webers/m^2." When expressing a range of values, write "7 to 9" or "7–9," not "7$\sim$9."

A parenthetical statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). (A parenthetical sentence is punctuated within the parentheses.) In American English, periods and commas are located within quotation marks, like “this period.” Other punctuation is placed “outside”! Avoid contractions; for example, write “do not” instead of “don’t.” The serial comma is preferred: “A, B, and C” instead of “A, B and C.”

If you wish, you may write in the first person singular or plural form using the active voice (“I observed that . . .” or “We observed that . . .” instead of “It was observed that . . .”). Remember to check spelling. If your native language is not English, please have a native English-speaking colleague to carefully proofread your paper.

VII. Math

A. Equations

Number equations consecutively with equation numbers in parentheses flush with the right margin, as appears in (1). Refer to “(1),” not “Eq. (1)” or “equation (1),” except at the beginning of a sentence: “Equation (1) is . . . .” To make your equations more compact, you may use the solidus (/), the exp function, or appropriate exponents. Use parentheses to avoid ambiguities in denominators. Punctuate equations when they are part of a sentence, as in

$$E = mc^2. \tag{1}$$

Be sure to define the symbols in your equation before the equation appears or immediately following. Italicize symbols (T might refer to temperature, but T is the unit tesla).

B. LaTeX-Specific Advice

Use “soft” (e.g., `\eqref{Eq}`) cross references instead of “hard” references (e.g., `(1)`). This will make it possible to combine sections, add equations, or change the order of figures or citations without having to manually change equation references.

Do not use the `{eqnarray}` equation environment. Use `{align}` or `{IEEEeqnarray}` instead. The `{eqnarray}` environment leaves unsightly spaces around relation symbols.

Note that the `{subequations}` environment in LaTeX will increment the main equation counter even when there are no equation numbers displayed.

BibTeX only functions in conjunction with local .bib files. If you use BibTeX to produce the bibliography you must attach the .bib files.

LaTeX can’t read your mind. If you assign the same label to both a subsubsection and a table, you may find that Table I has been cross referenced as Table IV-B3.

LaTeX does not have precognitive abilities. If you put a `\label` command before the command that updates the counter it’s supposed to be using, the label will pick up the last counter to be cross referenced instead. In particular, a `\label` command should not go before the caption of a figure or a table.

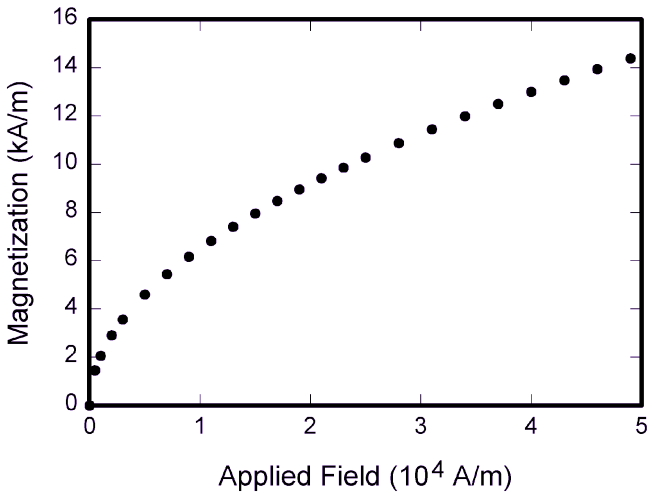

Fig. 1. Magnetization as a function of applied field. It is good practice to explain the significance of the figure in the caption.

Do not use `\nonumber` inside the `{array}` environment. It will not stop equation numbers inside `{array}` and it might stop a wanted equation number in the surrounding equation.

If you are submitting your paper to a colorized journal, you can use the following two lines at the start of the article to ensure its appearance resembles the final copy:

```
\documentclass[journal,twoside,web]{ieeecolor}
\usepackage{Journal_Name}
```

VIII. Units

Use either SI (MKS) or CGS as primary units. (SI units are strongly encouraged.) English units may be used as secondary units (in parentheses). For example, write “1 kg (2.2lb).” An exception exists for when English units are used as identifiers in commercial products, such as a “3½-in disk drive.” Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation.

The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T, either refer to magnetic flux density B or magnetic field strength symbolized as $\mu_0 H$. Use the center dot to separate compound units, e.g., “A·m^2.”

IX. Guidelines for Graphics Preparation and Submission

A. Types of Graphics

The following list outlines the different types of graphics published in IEEE journals. They are categorized based on their construction, and use of color / shades of gray:

1) Color/Grayscale figures: Figures that are meant to appear in color, or shades of black/gray. Such figures may include photographs, illustrations, multicolor graphs, and flowcharts.

TABLE I
UNITS FOR MAGNETIC PROPERTIES

Symbol	Quantity	Conversion from Gaussian and CGS EMU to SI [a]
Φ	magnetic flux	1 Mx $\rightarrow 10^{-8}$ Wb $= 10^{-8}$ V·s
B	magnetic flux density, magnetic induction	1 G $\rightarrow 10^{-4}$ T $= 10^{-4}$ Wb/m^2
H	magnetic field strength	1 Oe $\rightarrow 10^3/(4\pi)$ A/m
m	magnetic moment	1 erg/G $=$ 1 emu $\rightarrow 10^{-3}$ A·m^2 $= 10^{-3}$ J/T
M	magnetization	1 erg/(G·cm^3) $=$ 1 emu/cm^3 $\rightarrow 10^3$ A/m
$4\pi M$	magnetization	1 G $\rightarrow 10^3/(4\pi)$ A/m
σ	specific magnetization	1 erg/(G·g) $=$ 1 emu/g $\rightarrow$ 1 A·m^2/kg
j	magnetic dipole moment	1 erg/G $=$ 1 emu $\rightarrow 4\pi \times 10^{-10}$ Wb·m
J	magnetic polarization	1 erg/(G·cm^3) $=$ 1 emu/cm^3 $\rightarrow 4\pi \times 10^{-4}$ T
χ, κ	susceptibility	1 $\rightarrow 4\pi$
χ_ρ	mass susceptibility	1 cm^3/g $\rightarrow 4\pi \times 10^{-3}$ m^3/kg
μ	permeability	1 $\rightarrow 4\pi \times 10^{-7}$ H/m $= 4\pi \times 10^{-7}$ Wb/(A·m)
μ_r	relative permeability	$\mu \rightarrow \mu_r$
w, W	energy density	1 erg/cm^3 $\rightarrow 10^{-1}$ J/m^3
N, D	demagnetizing factor	1 $\rightarrow 1/(4\pi)$

Vertical lines are optional in tables. Statements that serve as captions for the entire table do not need footnote letters.
[a]Gaussian units are the same as cg emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted; Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

2) Line Art figures: Figures that are composed of only black lines and shapes. These figures should have no shades or halftones of gray, only black and white.

3) Author photos: Not allowed for papers in TMI.

4) Tables: Data charts which are typically black and white, but sometimes include color.

B. Multipart figures

Multipart figures are comprised of more than one sub-figure presented together. If a multipart figure is made up of multiple figure types (one part is lineart, and another is grayscale or color) the figure should meet the strictest applicable guidelines.

C. File Formats For Graphics

Format and save your graphics as one of the following approved file types: PostScript (.PS), Encapsulated PostScript (.EPS), Tagged Image File Format (.TIFF), Portable Document Format (.PDF), Portable Network Graphics (.PNG), or Metapost (.MPS). After the paper is accepted, any included graphics must be submitted alongside the final manuscript files.

D. Sizing of Graphics

Most charts, graphs, and tables are one column wide (3.5 inches / 88 millimeters) or page wide (7.16 inches / 181 millimeters). The maximum depth of a graphic is 8.5 inches (216 millimeters). When choosing the depth of a graphic, please allow space for a caption. Authors are allowed to size figures between column and page widths, but it is recommended not to size figures less than column width unless necessary.

E. Resolution

The proper resolution of your figures will depend on the type of figure it is as defined in the "Types of Figures" section. Author photographs, color, and grayscale figures should be at least 300dpi. Lineart, including tables should be a minimum of 600dpi.

F. Vector Art

While IEEE does accept and even recommends that authors submit artwork in vector format, it is our policy is to rasterize all figures for publication. This is done in order to preserve figures' integrity across multiple computer platforms.

G. Colorspace

The term colorspace refers to the entire sum of colors that can be represented within a given medium. For our purposes, the three main colorspaces are grayscale, RGB (red/green/blue) and CMYK (cyan/magenta/yellow/black). RGB is generally used with on-screen graphics, whereas CMYK is used for printing purposes.

All color figures should be generated in RGB or CMYK colorspace. Grayscale images should be submitted in grayscale colorspace. Line art may be provided in grayscale OR bitmap colorspace. Note that "bitmap colorspace" and "bitmap file format" are not the same thing. When bitmap colorspace is selected, .TIF/.TIFF are the recommended file formats.

H. Accepted Fonts Within Figures

When preparing your graphics IEEE suggests that you use of one of the following Open Type fonts: Times New Roman, Helvetica, Arial, Cambria, and Symbol. If you are supplying EPS, PS, or PDF files all fonts must be embedded. Some fonts may only be native to your operating system; without the fonts embedded, parts of the graphic may be distorted or missing.

A safe option when finalizing your figures is to strip out the fonts before you save the files, creating "outline" type. This converts fonts to artwork that will appear uniformly on any screen.

I. Using Labels Within Figures

1) Figure Axis labels: Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the quantity "Magnetization," or "Magnetization M," not just "M." Put units in parentheses. Do not label axes only with units. As in Fig. 1, for example, write "Magnetization (A/m)" or "Magnetization (A·m^{-1})," not just "A/m." Do not label axes with a ratio of quantities and units. For example, write "Temperature (K)," not "Temperature/K."

Multipliers can be especially confusing. Write "Magnetization (kA/m)" or "Magnetization (10^3 A/m)." Do not write "Magnetization (A/m) $\times$ 1000" because the reader would not know whether the top axis label in Fig. 1 meant 16000 A/m or 0.016 A/m. Figure labels should be legible, approximately 8 to 10 point type.

2) Subfigure Labels in Multipart Figures and Tables: Multipart figures should be combined and labeled before final submission. Labels should appear centered below each subfigure in 8 point Times New Roman font in the format of (a) (b) (c).

J. Referencing a Figure or Table Within Your Paper

When referencing your figures and tables within your paper, use the abbreviation "Fig." even at the beginning of a sentence. Do not abbreviate "Table." Tables should be numbered with Roman numerals.

K. Submitting Your Graphics

Format your paper with the graphics included within the body of the text as you would expect to see the paper in print. Please do this at each stage of the review, from first submission to final files. For final files only, after the paper has been accepted for publication, figures should also be submitted individually in addition to the manuscript file using one of the approved file formats. Place a figure caption below each figure; place table titles above the tables. Do not include captions or borders in the uploaded figure files.

L. File Naming

Figures (line artwork or images) should be named starting with the first 5 letters of the corresponding author's last name. The next characters in the filename should be the number that represents the figure's sequential location in the article. For example, in author "Anderson's" paper, the first three figures might be named ander1.tif, ander2.tif, and ander3.ps.

Tables should contain only the body of the table (not the caption) and should be named similarly to figures, except that '.t' is inserted in-between the author's name and the table number. For example, author Anderson's first three tables would be named ander.t1.tif, ander.t2.ps, ander.t3.eps.

Author photographs or biographies are not permitted in IEEE TMI papers.

M. Checking Your Figures: The IEEE Graphics Analyzer

The IEEE Graphics Analyzer enables authors to pre-screen their graphics for compliance with IEEE Transactions and Journals standards before submission. The online tool, located at http://graphicsqc.ieee.org/, allows authors to upload their graphics in order to check that each file is the correct file format, resolution, size and colorspace; that no fonts are missing or corrupt; that figures are not compiled in layers or have transparency, and that they are named according to the IEEE Transactions and Journals naming convention. At the end of this automated process, authors are provided with a detailed report on each graphic within the web applet, as well as by email.

For more information on using the Graphics Analyzer or any other graphics related topic, contact the IEEE Graphics Help Desk by e-mail at graphics@ieee.org.

N. Color Processing/Printing in IEEE Journals

All IEEE Transactions, Journals, and Letters allow an author to publish color figures on IEEE Xplore® at no charge, and automatically convert them to grayscale for print versions. In most journals, figures and tables may alternatively be printed in color if an author chooses to do so. Please note that this service comes at an extra expense to the author. If you intend to have print color graphics, include a note with your final paper indicating which figures or tables you would like to be handled that way, and stating that you are willing to pay the additional fee.

X. Some Common Mistakes

The word "data" is plural, not singular. The subscript for the permeability of vacuum μ_0 is zero, not a lowercase letter "o." Use the word "micrometer" instead of "micron." A graph within a graph is an "inset," not an "insert." The word "alternatively" is preferred to the word "alternately" (unless you really mean something that alternates). Use the word "whereas" instead of "while" (unless you are referring to simultaneous events). Do not use the word "essentially" to mean "approximately" or "effectively." Do not use the word "issue" as a euphemism for "problem." When compositions are not specified, separate chemical symbols by en-dashes; for example, "NiMn" indicates the intermetallic compound $\mathrm{Ni}_{0.5}\mathrm{Mn}_{0.5}$ whereas "Ni–Mn" indicates an alloy of some composition $\mathrm{Ni}_x\mathrm{Mn}_{1-x}$.

Be aware of the different meanings of the homophones "affect" (usually a verb) and "effect" (usually a noun), "complement" and "compliment," "discreet" and "discrete," "principal" (e.g., "principal investigator") and "principle" (e.g., "principle of measurement"). Do not confuse "imply" and "infer."

Prefixes such as "non," "sub," "micro," "multi," and "ultra" are not independent words; they should be joined to the words they modify, usually without a hyphen. There is no period after the "et" in the Latin abbreviation "*et al.*" (it is also italicized). The abbreviation "i.e.," means "that is," and the abbreviation "e.g.," means "for example" (these abbreviations are not italicized).

A general IEEE styleguide is available at http://www.ieee.org/web/publications/authors/transjnl/index.html.

XI. Conclusion

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

Appendix and the Use of Supplemental Files

Appendices, if needed, appear before the acknowledgment. If an appendix is not critical to the main message of the manuscript and is included only for thoroughness or for reader reference, then consider submitting appendices as supplemental materials. Supplementary files are available to readers through IEEE *Xplore*® at no additional cost to the authors

but they do not appear in print versions. Supplementary files must be uploaded in ScholarOne as supporting documents, but for accepted papers they should be uploaded as Multimedia documents. Refer readers to the supplementary files where appropriate within the manuscript text using footnotes. [1]

ACKNOWLEDGMENT

The preferred spelling of the word "acknowledgment" in American English is without an "e" after the "g." Use the singular heading even if you have many acknowledgments. Avoid expressions such as "One of us (S.B.A.) would like to thank . . . ." Instead, write "F. A. Author thanks . . . ." In most cases, sponsor and financial support acknowledgments are placed in the unnumbered footnote on the first page, not here.

REFERENCES AND FOOTNOTES

A. References

All listed references must be cited in text at least once. Use number citations that are placed in square brackets and inside the punctuation.

Multiple references are each numbered with separate brackets. When citing a section in a book, please give the relevant page numbers. In text, refer simply to the reference number. Do not use "Ref." or "reference" except at the beginning of a sentence: "Reference [**?**] shows . . . .'

Reference numbers are set flush left and form a column of their own, hanging out beyond the body of the reference. The reference numbers are on the line, enclosed in square brackets. In all references, the given name of the author or editor is abbreviated to the initial only and precedes the last name. List the names of all authors if there are six or fewer coauthors, otherwise list the primary author's name followed by *at al.* Use commas around Jr., Sr., and III in names. Abbreviate conference titles. When citing IEEE transactions, provide the issue number, page range, volume number, year, and/or month if available. When referencing a patent, provide the day and month of issue or application. References may not include all information; please obtain and include relevant information. Do not combine references. There must be only one reference with each number. If there is a URL included with the print reference, it can be included at the end of the reference.

Other than books, capitalize only the first word in a paper title, except for proper nouns and element symbols. For papers published in translation journals, please give the English citation first, followed by the original foreign-language citation. See the end of this document for formats and examples of common references. For a complete discussion of references and their formats, see the IEEE style manual at https://journals.ieeeauthorcenter.ieee.org/your-role-in-article-production/ieee-editorial-style-manual/.

[1]Supplementary materials are available in the supporting documents/multimedia tab. Further instructions on footnote usage are in the Footnotes section on the next page.

B. Footnotes

Number footnotes separately using superscripts.[2] It is recommended that footnotes be avoided (except for the unnumbered footnote with the receipt date on the first page). Instead, try to integrate the footnote information into the text. Use letters for table footnotes (see Table I).

APPENDIX I
REFERENCES

- *Basic format for books:*
  J. K. Author, "Title of chapter in the book," in *Title of His Published Book, x*th ed. City of Publisher, (only U.S. State), Country: Abbrev. of Publisher, year, ch. x, sec. x, pp. *xxx–xxx.*
  See [**?**], [**?**].
- *Basic format for periodicals:*
  J. K. Author, "Name of paper," *Abbrev. Title of Periodical*, vol. *x, no. x*,pp. *xxx–xxx,* Abbrev. Month, year, DOI. 10.1109.*XXX*.123456.
  See [**?**]– [**?**].
- *Basic format for reports:*
  J. K. Author, "Title of report," Abbrev. Name of Co., City of Co., Abbrev. State, Country, Rep. *xxx*, year.
  See [**?**], [**?**].
- *Basic format for handbooks:*
  Name of Manual/Handbook, x ed., Abbrev. Name of Co., City of Co., Abbrev. State, Country, year, pp. *xxx–xxx.*
  See [**?**], [**?**].
- *Basic format for books (when available online):*
  J. K. Author, "Title of chapter in the book," in *Title of Published Book*, xth ed. City of Publisher, State, Country: Abbrev. of Publisher, year, ch. x, sec. x, pp. *xxx–xxx.* [Online]. Available: http://www.web.com
  See [**?**]– [**?**].
- *Basic format for journals (when available online):*
  J. K. Author, "Name of paper," *Abbrev. Title of Periodical*, vol. x, no. x, pp. *xxx–xxx*, Abbrev. Month, year. Accessed on: Month, Day, year, DOI: 10.1109.*XXX*.123456, [Online].
  See [**?**]– [**?**].
- *Basic format for papers presented at conferences (when available online):*
  J.K. Author. (year, month). Title. presented at abbrev. conference title. [Type of Medium]. Available: site/path/file
  See [**?**].
- *Basic format for reports and handbooks (when available online):*
  J. K. Author. "Title of report," Company. City, State, Country. Rep. no., (optional: vol./issue), Date. [Online] Available: site/path/file
  See [**?**], [**?**].
- *Basic format for computer programs and electronic documents (when available online):*
  Legislative body. Number of Congress, Session. (year,

[2]Place the actual footnote at the bottom of the column in which it is cited; do not put footnotes in the reference list (endnotes).

month day). *Number of bill or resolution*, *Title*. [Type of medium]. Available: site/path/file
NOTE: **ISO recommends that capitalization follow the accepted practice for the language or script in which the information is given.**
See [**?**].

- *Basic format for patents (when available online):*
  Name of the invention, by inventor's name. (year, month day). Patent Number [Type of medium]. Available: site/path/file
  See [**?**].
- *Basic formatfor conference proceedings (published):*
  J. K. Author, "Title of paper," in *Abbreviated Name of Conf.*, City of Conf., Abbrev. State (if given), Country, year, pp. *xxxxxx.*
  See [**?**].
- *Example for papers presented at conferences (unpublished):*
  See [**?**].
- *Basic format for patents*:
  J. K. Author, "Title of patent," U.S. Patent *x xxx xxx*, Abbrev. Month, day, year.
  See [**?**].
- *Basic format for theses (M.S.) and dissertations (Ph.D.):*
  1) J. K. Author, "Title of thesis," M.S. thesis, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.
  2) J. K. Author, "Title of dissertation," Ph.D. dissertation, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.

  See [**?**], [**?**].
- *Basic format for the most common types of unpublished references:*
  1) J. K. Author, private communication, Abbrev. Month, year.
  2) J. K. Author, "Title of paper," unpublished.
  3) J. K. Author, "Title of paper," to be published.

  See [**?**]– [**?**].
- *Basic formats for standards:*
  1) *Title of Standard*, Standard number, date.
  2) *Title of Standard*, Standard number, Corporate author, location, date.

  See [**?**], [**?**].
- *Article number in reference examples:*
  See [**?**], [**?**].
- *Example when using et al.:*
  See [**?**].

REFERENCES

[1] Faluk M, De Jesus O. "Saccular Aneurysm" in *Statpearls*. Treasure Island, FL, USA: StatPearls Publishing; 2022 Jan- [Updated 2022 May 8]. [Online]. Available: https://www.ncbi.nlm.nih.gov/books/NBK557867/.

[2] Chalouhi N, Hoh BL, Hasan D. Review of Cerebral Aneurysm Formation, Growth, and Rupture. Stroke. 2013;44(12):3613-22. Https://www.ahajournals.org/doi/abs/10.1161/STROKEAHA.113.002390.

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