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ABSTRACT

The Einstein Telescope (ET) is a project aiming to realize a facility to host a gravitational wave (GW) detector of the third generation. The new instrument will change our vision of the Universe by observing millions of GW signals emitted during the coalescence of stellar and intermediate-mass black hole binary systems. It will permit to shed light on the first phase of the Universe formation and it will contribute to solving the dark matter enigma. The new GW detector is conceived as a series of six nested Michelson interferometers forming a triangle of 10 km side. The laser light biasing the interferometers must propagate in large ultra-high vacuum (UHV) tubes in order to reduce the noise induced by the residual gas pressure fluctuations, setting a requirement on the residual pressure in the 10^{-10} mbar range. The vacuum system will be made of a pipe with a 1 m diameter and an overall length of 120 km, making ET one of the largest UHV systems ever made. The giant UHV project asks for attentive optimization of material choice, manufacturing processes, post-processing treatments of the tubes, and pumping systems in order to find a cost-effective solution. In this article, we shortly review the vacuum solution adopted in the case of the second generation of GW detectors. After a general description of the main elements that constitute the ET vacuum system, the detailed design being the subject of the next 3 years of work, we will present a refined calculation of the noise due to residual-gas pressure fluctuations in the ET beam pipe.

I. INTRODUCTION

The second generation gravitational wave (GW) detectors, Advanced Virgo[1] and Advanced LIGO,[2] have achieved the crucial goal to detect the first GW signals. At present, the signal catalog[3] includes 90 GW events generated by the coalescence of binary systems formed by black holes, black hole and neutron star, and binary neutron stars. These detections enlighten several open questions in astrophysics as, for example, the distribution of the intermediate mass binary black holes, the nature of the central engine triggering the short gamma ray bursts, and even opening a new way to determine the Hubble constant. Thus, the GW astronomy is born with the second generation of detectors, detecting even new puzzling events, which require new measurements to be carried on at a higher signal-to-noise ratio (SNR).[4]

Although Advanced Virgo and LIGO will continue to evolve increasing their sensitivity, in the long term, the improvement of the performance of these detectors will be constrained by the hosting infrastructure and the observed signals will be related mainly to signals emitted in the local Universe.

To push the Universe exploration up to the Universe border, the GW scientific community is proposing 3^{rd} generation GW observatories, one in USA named Cosmic Explorer (CE, for details on CE see Ref. 5) and one in Europe called Einstein Telescope (ET).[6] The aims of ET are:

(a) to increase the sensitivity at least one order of magnitude with respect to the nominal sensitivity of advanced detectors;
(b) to widen the frequency band observation;
(c) to achieve higher sensitivity at low frequency (few Hz) for studying massive (or intermediate mass) black holes up to the border of the observable Universe.

While with the second generation of detectors, the main results can be obtained by operating the detectors as a network, the new instrument can make science in a standalone configuration, being capable of localizing the source and studying the polarization content of the signal. The ET facility is conceived to have a lifetime of several decades (50 years at least).

In the low frequency range, the noise source externals to the detector are the micro-seism, the pressure fluctuation of the atmosphere, and the so-called Newtonian noise: to limit these noises ET will be installed underground. The new GW observatory will be the combination of three detector areas, each of them hosting a pair of Michelson interferometers: ET-LF optimized to detect signals in the low frequency band (3–40 Hz) with optical mirrors cooled at cryogenic temperature; ET-HF, operating at room temperature, with enhanced sensitivity in the high frequency band (40 Hz–10 kHz). As in the case of LIGO and Virgo, the light emitted by a super-stabilized laser will propagate in ultra-high vacuum (UHV) tubes bouncing several times among heavy mirrors of ultra-high quality. The mirrors will be placed in three experimental areas at the vertices of a 10-km side equilateral triangle.

The expected cost of the whole project is of the order of 2 billion euros,[7] half of which will be devoted to the civil engineering activity to design and build the underground infrastructure. The second investment of the project will be devoted to the vacuum system, which has to include the construction and installation and test of 120 km UHV beam pipes of ∼1 m diameter. The paper concerns this second item of the project and it is organized as follows: in Sec. II, we review the techniques used to build the UHV pipes in the case of the detectors of the second; in Sec. III, we discuss the requirements of the ET vacuum system, while in Sec. IV, we present a refined calculation to evaluate the ET partial pressure requirements. The final section is devoted to the discussion and conclusions.

II. VACUUM PIPES OF GW DETECTORS

The construction of the beam pipes of the GW vacuum system is a major engineering challenge with technical and financial implications. As we anticipated in the previous section, the laser light pumped into the interferometers must propagate in an UHV environment. The reason is to keep low enough the fluctuation of the effective refractive index of residual gas species along the light path since the random change in the column density of gas particles can mimic the expected GW signals, spoiling the detector performance. UHV is crucial also to preserve the mirror's cleanliness, reduce the gas damping of the suspended optics, and contribute to acoustic isolation of the detector. The design of the ET vacuum system asks for careful optimization of the material choice, the production processes, the characterization, and the thermal treatments of the pipes fulfilling the requirements of the GW interferometer. In the past, the design of the second generation GW detectors followed a similar optimization path and we intend to take advantage of the gained experience. Thus, as first we recall the solutions adopted in Virgo, LIGO, the detector KAGRA in Japan and the interferometer GEO600 installed in Germany.

Advanced Virgo[1] is a single interferometer of 3-km long arms, located in Cascina (Pisa), Italy. The Advanced LIGO project includes two identical detectors with 4 km arms: the first one is located in Livingston (Louisiana state—USA) while the second is in Hanford (Washington state—USA).[2] GEO600[8] has shorter arms, 600 m, and it is located near Hannover (Germany). Finally, KAGRA[9] is the latest project, classified as a detector of 2.5 generation: it is installed underground near the Kamioka mine of the Gifu prefecture of Japan. The interferometer arms are 3 km long and the mirrors are kept at cryogenic temperatures.

The technologies used for building the UHV pipes are different for all four detectors. All the pipes are made of stainless steel: AISI 316L in the case of GEO600, AISI 304L for all the others. The vacuum pipes were composed of modules. Virgo produced tube modules 1.2 m diameter, 15 m long,[10] starting from 4 mm steel sheets with 0.7 m spaced stiffening rings. The modules include a 2 mm thick hydro-formed bellow. LIGO produced in situ modules 1.24 m diameter, 16 m long tubes, starting from a 3.3 mm thick steel coil welded in spiral.[11] In GEO600,[12] a completely different solution was adopted: from 0.8 mm thick sheets they produced 0.6 m diameter, 4.5 m long modules, stiffened by deep hydro-formed corrugation. In the case of KAGRA,[13] the 0.8 m diameter, 12 meter long modules were manufactured from rather thick steel (8 mm) such that stiffening rings were not required. All these information are collected in Table I.

The requirement on the residual pressure of the aforementioned UHV systems must be in the range of 10^{-9}–10^{-11} mbar; this is obtained by reducing the gas load and increasing the effective pumping speed. After in situ bakeout, the gas load is dominated by hydrogen outgassing from the walls of the vacuum vessel. The methods applied to reduce the H_2 outgassing in the case of stainless steel include *ex situ* heating at high temperatures in a vacuum or air furnace (*vacuum or air firing*) and in situ backout at medium temperatures. Even in the case of the thermal treatments, the applied method changes from one 2G detector to another: Virgo used air firing at 400 °C on each module, LIGO fired in air directly the steel coils at 455 °C, while KAGRA and GEO used a quite low temperature air-firing (200 °C). After the installation of the whole pipeline, once under vacuum, further thermal treatment was applied for backout purpose. The pipe was heated by the Joule effect flowing ∼2000 A through it, to reduce the water outgassing rate. This last operation was not performed in KAGRA since they electro-polished the inner wall of the tubes. Details concerning the second generation GW detectors vacuum pipes are reported in Table I including a pipe cost per meter estimate for each solution. These cost estimates must be regarded as purely indicative since

TABLE I. Comparison of the second GW detectors vacuum systems. The table reports the main beam pipes construction and thermal treatments parameters. Also, a very rough cost per meter estimation is given (see warning note in the text).

	Virgo	LIGO	KAGRA	GEO600
Material (AISI)	304L	304L	304L	316L
Length (km)	6	2×8	6	1.2
Diameter (m)	1.2	1.24	0.81	0.6
Section length (m)	15	16	12	4.5
Thickness (mm)	4	3.23	8	0.8
Tube type	Sheet welded	Spiral welded	Sheet welded	Deep corrug.
Pipe cost (euro/m)	2400	2200	4745[a]	440
Vacuum H_2O (mbar)	5.6×10^{-10}	1.3×10^{-10}	1.5×10^{-8}	1.5×10^{-7}[b]
Pumps distance (m)	600	2000	600	600
Firing temp (^oC)	400	455	200	200
Firing duration	5 days	36 h	20 h	48 h
Bakeout temp (^oC)	150	160	No (electro-polishing)	250
Bakeout duration	1 week	3 weeks		5 days
Pumps types	TMP, Ion+Ti Sub.	TMP, Ion+Cryo	TMP, Ion	TMP

[a]This include bellows SS316L, flanges, crow clamp, EP-finished, baking.
[b]Pressure in 2021 before pumps upgrade.

they refer to different construction times and they may not include the same items/procedures.

III. ET VACUUM SYSTEM

The vacuum system of ET, once assembled in the full configuration, will be among the largest UHV apparatus in the world. Assuming for the ET vacuum pipes, 1 m diameter and a total length of 120 km, the UHV volume will be 9.4×10^4 m^3 with an inner surface of the tube surface of 3.8×10^5 m^2. In the hypothetical case of adopting the Virgo solution to build it, the rough estimation of the cost is of the order 560 million euros. A first evaluation of the requirements concerning the residual partial pressures in the tube was done in 2011 and is reported in the first conceptual design of ET. Here, we report these values as reference: 10^{-10} mbar for H_2, 5×10^{-11} mbar for water, and less than 10^{-14} mbar for hydrocarbons with molecular mass in the range of hundred and more.

These values should guarantee a limit in terms of spectral strain sensitivity of ET due to residual gas fluctuations ranging around 10^{-25} $1/\sqrt{(Hz)}$. Again, if we assume a Virgo-like design, we estimate that ET would need ∼13 000 tons of raw steel to produce 8000 modules 15 m long (including the bellow for thermal expansion). To produce all the modules in a time of the order of 3 years, the production and installation rate should be ∼8 modules/day (including an extensive quality control check for each module). For what concern the air firing to deplete the hydrogen content in the bulk material, assuming that the stainless steel will be austenitic, it would require 10 ovens, each processing 4 tube modules at a time, operating for ∼3 years 24/7, while the backout, achieved by flowing high electrical current directly through the pipe, will last several days with heat dissipation of 250 W/m to reach a vessel temperature of 150 °C. According to the ET Design Report Update,[14] we assume a pumping station every 500 m (for a total of 240 stations and 480 gate valves DN250) with an effective speed of 5000 l/s . The interferometer arm, 10 km long, should be segmented, using UHV valves, in at least three parts. In addition, we need valves to isolate the beam pipe from the vacuum towers hosting the mirrors: we end up with a need to install 72 gate valves DN1000. The monitor of the vacuum system will account for ∼200 Residual Gas Analysers (RGA) and ∼1000 gauges.

The outcome of this rough evaluation brings us to the obvious conclusion that we need to do a huge effort to optimize the choice of materials, manufacturing processes and treatments on the tubes, in order to find a cost-effective solution. The material selection is one of the items where to concentrate the effort of an R&D program, both for reducing the cost and speed up the de-hydrogenation process.

IV. PARTIAL PRESSURE REQUIREMENTS OF THE ET BEAM PIPES

In this section, we set new values for the requirements on the ET beam pipe partial pressures by following a slight different approach to compute the values reported in Ref. 14. The noise contribution to the sensitivity of a GW detector due to residual gas fluctuations in the UHV pipe arms is computed using the formula first derived in Ref. 15,

$$S_L(f) = \frac{(4\pi\alpha)^2}{v_0} \int_0^{L_{tot}} \frac{\rho(z) e^{-2\pi f w(z)/v_0}}{w(z)} dz, \quad (1)$$

where S_L is the power spectral density of the fluctuations of the optical path of a single arm of the interferometer, f is the frequency, α is the optical polarizability of the gas molecules, v_0 is the average gas molecules speed, ρ is the molecules number density, $w(z)$ the laser beam radius, function of the arm coordinate, and L_{tot} is the interferometer arm length. Several experimental groups verified this formula by increasing the pressure in beam pipe

TABLE II. High and low frequency ET parameters used for the calculation of the gas induced noise. R_1 and R_2 refer to the curvature radius of the mirror arm cavities on which depends the laser beam radius profile along the pipe.

	ET high freq.	ET low freq.
Arm length (km)	10	10
Wavelength (μm)	1.064	1.55
Pipe diameter (m)	1	1
Effective pumping speed (l/s)	5000	5000
Distance between pumps (m)	500	500
R1 mirrors radius (m)	5070	5580
R2 mirrors radius (m)	5070	5580
Waist diameter (m)	0.0141	0.0289
P H_2 (mbar)	1×10^{-10}	1×10^{-10}
P H_2O (mbar)	2×10^{-11}	2×10^{-11}

interferometers and measuring the change in the sensitivity curve.[16–18] In the ET design report,[6] the requirements on the partial pressures of the beam pipes have been set using Eq. (1), under the assumption of a constant pressure profile along the pipe. However, due to pipe vacuum conductance, the pressure is a function of the arm coordinate with a minimum in correspondence with the pumping stations and a maximum in the middle of two adjacent pumps. Assuming a pipe diameter D, a distance between adjacent pumps equal to L, a specific outgassing rate q, a total outgassing rate Q for the pipe of length $L/2$ and S (l/s) the effective pumping speed of each station, the minimum pressure is $P_{\min} = 2^{*}Q/S$ while the maximum pressure is $P_{\max} = P_{\min} + Q/2C$ where C is the conductance of the pipe with length L/2. The conductance of a circular pipe with diameter D and length L, for a gas specie g, is $C_g = 3.81 \times \sqrt{TM_g}D^3/L$

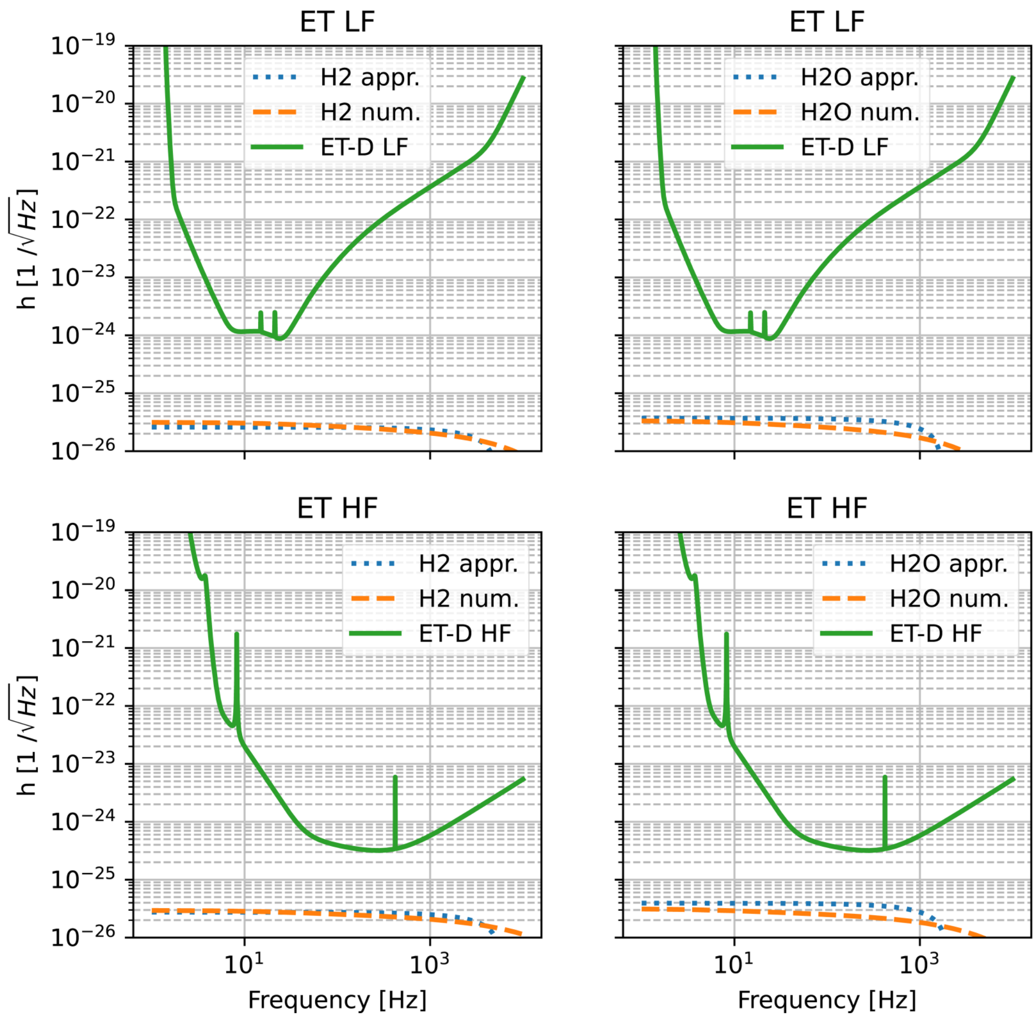

FIG. 1. Noise contribution of residual gases hydrogen and water to the ET sensitive curve. The continuous lines are the ET-D sensitivity curves, the dotted lines are the noise calculated with the approximated formula while the dashed lines are calculated with a more accurate numerical integration of Eq. (1).

([l/s])[19] where T is the temperature in kelvin, M is the molecular mass, and D and L are expressed in cm. The pressure profile along the tube can be easily derived as the solution of a second order differential equation describing the balance of fluxes and is given in Eq. (2),

$$P(x) = P_{\min} + \frac{2Q}{C}\left(\frac{x}{L} - \frac{x^2}{L^2}\right). \qquad (2)$$

Taking into account this pressure variation in Eq. (1), we have derived the new values for the partial pressure for both ET-LF and ET-HF. In the calculations, we have assumed as detector parameters those reported in Table II.

The noise contribution has been calculated in two ways:

- by numerical integration of Eq. (1) assuming a pressure profile calculated with Eq. (2),
- by a first order expansion of the exponential function in Eq. (1), assuming a constant pressure equal to maximum partial pressure values. This is the method adopted in the ET Design Report.

In Fig. 1, we show the residual gas noise contribution in the cases of hydrogen and water, the two main gas species expected in the pipe, for both high and low frequency interferometers. The noise curves have been obtained assuming pumping station set with a distance periodicity of 500 m, an effective gas independent pumping speed of 5000 l/s, a hydrogen outgassing rate of 1.9×10^{-14} mbar l/(s cm^2), and a water outgassing rate of 2×10^{-15} mbar l/(s cm^2). The assumed values of the specific outgassing rates are chosen in such a way as to have maximum pressures in the vessel equal to the values reported in Table II.

In Table III, we report the noise contributions at the frequency of highest detector sensitivity in the low frequency (24 Hz) and high frequency bands (272 Hz), for hydrogen and water. In the same table, we report the ratio ET-D to residual gas induced noise obtained by the numerical calculation, being ET-D the reference sensitivity curve of ET.

In Fig. 2, we show the total noise due to gas pressure fluctuation assuming that the gas composition is a mixture of hydrogen and water according to the specific outgassing rates previously specified. This gives the beam pipe gas contribution to the ET noise budget. At the frequencies where the high and low frequency detectors sensitivity are highest, the ratio between the total noise of ET and the contribution given by the residual gas fluctuations are 10 and 21, respectively, while with the approximated calculation are 7 and 19.

TABLE III. Residual gas pressure noise contributions due to hydrogen and water. The values are obtained with approximated and numerical calculation and reported at 24 and 272 Hz, the frequency of highest sensitivity for ET-LF and ET-HF, respectively. The ratio ET-D to gas pressure noise obtained with numerical calculation, for hydrogen and water, is reported in the last two rows.

	ET low freq.	ET high freq.
H_2 approx. $(1/\sqrt{(Hz)})$	2.6×10^{-26}	2.7×10^{-26}
H_2 num. $(1/\sqrt{(Hz)})$	2.9×10^{-26}	2.4×10^{-26}
H_2O approx. $(1/\sqrt{(Hz)})$	3.7×10^{-26}	3.6×10^{-26}
H_2O num. $(1/\sqrt{(Hz)})$	2.9×10^{-26}	2.3×10^{-26}
ET-D/num. for H_2	30 (@24 Hz)	14 (@272 Hz)
ET-D/num. for H_2O	19 (@24 Hz)	9 (@272 Hz)

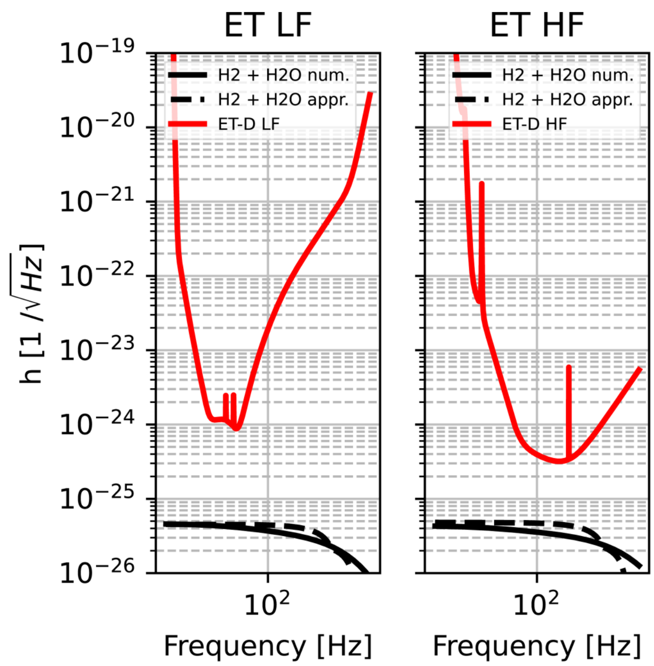

FIG. 2. Noise contribution due to the fluctuations of the residual gas pressure in the hypothesis of hydrogen and water gas composition. The red lines are the ET sensitivity curves, the black ones are the noise contribution due to the gas fluctuation computed by numerical integration of Eq. (1), the dashed lines are calculated using the linear expansion of the exponential function.

V. DISCUSSION AND CONCLUSION

In the paper, we describe the vacuum system of the third generation gravitational wave detector Einstein Telescope, which will be among the largest UHV system in the world. After a short review of what has been done for the operating second generation detectors, we give a description of the main components of the ET beam pipe vacuum system assuming a Virgo construction approach and we give an idea of the degassing thermal treatments required if, as Virgo, austenitic stainless steel is used. It comes out that one of the main challenges for the ET vacuum system is the optimization of the design and construction in order to minimize the cost. Since one of the expensive and time-consuming processes is indeed the de-hydrogenation of the steel, we are pushed to search for materials for which the procedure to deplete the hydrogen is less invasive or even not needed as could be the case of ferritic steel, as discussed at the LIGO-NSF Workshop on Large Ultrahigh-Vacuum Systems for Frontier Scientific Research Instrumentation.[20]

The main requirement for the design of a vacuum system for GW detectors is related to the contribution to the total noise due to the residual gas pressure fluctuation. Here, we presented a more accurate calculation and the corresponding contribution to the ET sensitivity curve. We have found that, for the high frequency interferometer, the limit due to the residual gas made of hydrogen and water is a factor of 10 lower than the ET sensitivity curve, improving by a factor of 1.4 the values reported in the ET conceptual design of 2020. Concerning the low frequency interferometer, the new results give a modest improvement by a factor of 1.1.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Aniello Grado: Conceptualization (lead); Data curation (lead); Formal analysis (equal); Writing – original draft (lead). **Emanuele Tofani:** Writing – review & editing (equal). **Marco Angelucci:** Writing – review & editing (supporting). **Roberto Cimino:** Methodology (equal); Writing – review & editing (equal). **Julien Gargiulo:** Writing – review & editing (equal). **Fedor Getman:** Writing – review & editing (equal). **Andrea Liedl:** Writing – review & editing (equal). **Luca Limatola:** Writing – review & editing (equal). **Vito Mennella:** Writing – review & editing (equal). **Antonio Pasqualetti:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Writing – review & editing (equal). **Fulvio Ricci:** Conceptualization (equal); Formal analysis (equal); Writing – review & editing (equal). **Daniel Sentenac:** Writing – review & editing (equal). **Luisa Spallino:** Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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