



Effects of Mandibular Extension on Pial Arteriolar Diameter Changes in Glucocorticoid-Induced Hypertensive Rats

Dominga Lapi¹, Maurizio Varanini², Lucrezia Galasso³, Martina Di Maro¹, Giuseppe Federighi³, Cristina Del Seppia², Antonio Colantuoni¹ and Rossana Scuri^{3*}

¹ Department of Clinical Medicine and Surgery, University of Naples Federico II, Naples, Italy, ² Institute of Clinical Physiology, National Council of Research (CNR), Pisa, Italy, ³ Department of Translational Research on New Technologies in Medicine and Surgery, University of Pisa, Pisa, Italy

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*Correspondence:

Rossana Scuri
rossana.scuri@unipi.it

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Previously, in normotensive rats, it has been observed that a repetitive sub-maximal mouth opening (mandibular extension, ME) obtained by placing a home-made U-shaped dilator between the superior and inferior dental arches of the rat caused modulation of pial arteriolar tone. The present study was aimed to characterize pial microcirculation in two different cortical brain regions and to assess the hemodynamic effects of a single or double ME on pial arteriolar rhythmic diameter changes in rats rendered hypertensive by dexamethasone administrations. Cranial windows were prepared on parietal and frontal region. Pial arterioles were classified by Strahler method in five orders by *in vivo* fluorescence microscopy technique associated with a computerized system that permits off-line measurements of arteriolar diameter changes. Two 10 min ME at 10 min interval were applied; then the animals were monitored for further 240 min. Dexamethasone-treated rats exhibited a marked arterial rarefaction and asymmetry of bifurcation in the pial microvascular networks more evident in the frontal region. Starting from ME1, in both cortical areas, the arterioles dilated, and the vasodilation became significant compared to baseline after ME2 for the entire observation period. The spectral analysis carried out on order 2 arteriolar diameter change tracings, showed that double ME increased the spectral density of the frequency components related to endothelial, neuronal and myogenic activities in both the cortical regions studied. In conclusion, double ME has a generalized effect in the cortical areas by restoring the physiological vasomotion of the pial arterioles that was severely impaired by the experimentally hypertension.

Keywords: mandibular extension, glucocorticoid-induced hypertension, rat pial microcirculation, Strahler's ordering scheme, arteriolar rhythmic diameter changes

INTRODUCTION

Recently, it has been shown that the mandibular extension (ME), consisting in a submaximal mouth opening for 10 min, placing a home-made U-shaped dilator between the superior and inferior dental arches of normotensive rats, caused cardiovascular effects and a pial arteriolar dilation due to the peripheral activation of the trigeminal nerve. These effects can be included in the so called

trigemino-cardiac reflex, which represents the expression of a neuroprotective central neurogenic reflex. A single ME produced prolonged (up to about 2 h) hypotensive and bradycardic effects, and a regulation of the arteriolar tone (Lapi et al., 2013, 2014), including an increase in the spectral density of the frequency components related to endothelial activity, that contributes to a modulation of the cerebral blood flow supply (Lapi et al., 2016). Similar effects on systemic arterial pressure and heart rate have been found in normotensive humans (Del Seppia et al., 2016, 2017).

In normotensive rats a double ME was also tested. A second ME applied 10 min after the first one prolonged (almost up to 4 h) the effects of the single ME on both blood pressure, heart rate and arteriolar tone (Lapi et al., 2017).

Interestingly, the vasodilation due to nitric oxide (NO) release by endothelial vascular cells was accompanied by changes in spontaneous oscillations of the arteriolar diameters; indeed, the spectral analysis, performed on 30 min tracings, showed that ME repetition produced a further increase in the very low frequency components related to endothelium-derived hyperpolarizing factor and endothelial nitric oxide synthase activity (endothelial-related frequency components), respectively (Stefanovska et al., 1999; Kvandal et al., 2003; Lapi et al., 2017) compared with those observed after a single ME.

As the aim to evaluate if ME procedure may be of potential relevance in brain injury states due to cardiovascular dysfunctions, in this paper we studied, *in vivo*, the effects of single and double ME in a pathophysiological condition such as hypertension, utilizing rats rendered hypertensive by dexamethasone treatment.

It is well known that the hypertensive state alters the structure of cerebral blood vessels and disrupts the complex vasoregulatory mechanisms that assure an adequate blood supply to the brain (Iadecola and Davisson, 2008; Grassia and Heistad, 2009). Therefore, we analyzed all frequency components in the spontaneous rhythmic diameter changes in rat pial arterioles before and after ME because single modifications of these frequency components can be relevant to clarify which mechanisms responsible for the arterial tone regulation are involved in hypertension and what alterations may be improved by ME. The analysis was carried out in pial arterioles perfusing the superficial layers of the parietal cortical region, where the trigeminal afferents project, and in the frontal region, taken as a cerebral area not involved in the trigeminal signal integration. The choice to study the changes of the arteriolar tone in two different cortical regions is crucial to clarify if ME influences the cerebral perfusion in all cerebral areas.

MATERIALS AND METHODS

Experimental Groups

Male Wistar rats, weighing 250–300g (Harlan, Udine, Italy) were used. The hypertension was induced by subcutaneous injection of dexamethasone (20 µg/Kg/day) (Sigma-Aldrich, St. Louis, MO, United States) for 7 days (Severino et al., 2002;

Iyer et al., 2010). All surgical procedures and experiments were carried out in anesthetized animals. The anesthesia was induced by alpha-chloralose (50 mg/Kg b.w.) plus urethane (600 mg/Kg b.w.) intraperitoneally administered and maintained with urethane alone administration (100 mg/kg, i.v., every hour).

The animals were randomly assigned to the following groups:

(a) Dexamethasone-treated rats subjected only to surgical procedures and observed for 300 min (Sham-operated, SO, $n = 5$);

(b) Dexamethasone-treated rats subjected to a single 10 min ME (ME1) and observed for 260 min after ME1 ($n = 5$) (Lapi et al., 2017);

(c) Dexamethasone-treated rats submitted to double ME (two 10 min MEs applied with a 10 min interval) ($n = 5$) (Lapi et al., 2017);

(d) Normotensive rats subjected only to surgical procedures and observed for 300 min ($n = 5$), utilized only for geometric characterization.

All experiments conform to the Guide for the Care and Use of Laboratory Animals of the National Institute of Health. The protocol was approved by the Committee on the Ethics of Animal Experiments of the University of Pisa and Italian Health Ministry (Permit Number: 156/2017-PR).

Mandibular Extension

The procedure for mandibular extension (ME) was previously described in Lapi et al. (2014). Briefly, a home-made U-shaped spring device, consisting of two thin layers covered with a silicone elastomer and an adjustable spring, allowing to open the month without muscle fatigue, was placed between the superior and inferior dental arches of the rats.

Animal Surgery

The surgical procedures were described in detail in previous papers (Lapi et al., 2013, 2014, 2017). Briefly, the rats under anesthesia were tracheotomized, intubated and consequently mechanically ventilated.

A catheter was placed in the left femoral artery to measure the arterial blood pressure and to obtain arterial blood samples every 60 min in order to monitor PaO₂, PaCO₂, and pH utilizing a blood gas/pH analyzer (ABL 80FLEX ANALYZER, RADIOMETER). pH, PaCO₂, and PaO₂ were maintained within physiological ranges (7.4 ± 0.01 for arterial pH, 35 ± 4 mmHg for PaCO₂ and 90 ± 5 mmHg for PaO₂).

A catheter was also placed in the right femoral vein to inject the fluorescent tracer fluorescein-isothiocyanate (FITC) (Sigma-Aldrich, St. Louis, MO, United States) every 120 min, and urethane every 60 min.

A heating stereotaxic frame was used to ensure the rats and maintain their body temperature constant at $37.0 \pm 0.5^\circ\text{C}$.

Moreover, two closed cranial windows were prepared to observe the pial microcirculation: the first was implanted above the left parietal cortex (4 mm × 5 mm: posterior 1.5 mm bregma and lateral 3 mm to the midline) and the second above the left frontal cortex (3 mm × 2 mm: posterior 2 mm to bregma and lateral 3 mm the midline). Each window was implanted after craniotomy; successively the dura

madre was removed and the windows closed with a 150 μm -thick quartz microscope coverglass assured to the bone with dental cement. A cold saline solution was suffused on the skull to prevent the overheating of the cerebral cortex during craniotomy. To maintain physiological conditions (intracranial pressure 5 ± 1 mmHg), the brain parenchyma was continuously superfused with artificial cerebrospinal fluid (aCSF, 0.5 mL/min) (Lapi et al., 2013, 2014).

Fluorescent Microscopy Technique and Microvascular Parameter Assessment

A fluorescence microscope (Leitz Orthoplan), fitted with long-distance objectives and eyepiece and a filter block (Ploemopak, Leitz), was utilized to visualize the pial microcirculation in Epi-illumination as reported in detail by Lapi et al. (2017).

Vessel diameter and length were measured off-line using a computer-assisted imaging software system (MIP Image, CNR, Institute of Clinical Physiology, Pisa, Italy) on videotaped images continuously acquired. Measurements were done by two independent “blinded” operators.

The maps of the arteriolar networks were obtained by stop-frame images and the classification of the pial arterioles in each map was made in accordance with the centripetal ordering scheme (Strahler method, modified according to diameter) (Kassab et al., 1993; Lapi et al., 2008).

In rat pial microvascular networks (Lapi et al., 2008), each blood vessel between two nodes of bifurcation is called a segment. In the Strahler's ordering scheme segments are connected in series so that they can be considered as a single tube in hemodynamics, called element. The S/E ratio was calculated as the ratio of the overall vessel segments (S) to the overall vessel elements (E) in any given order described.

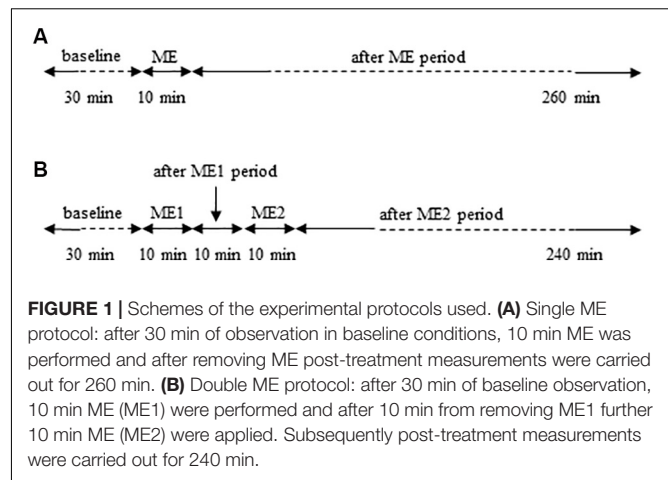
In each rat studied, several arterioles of different orders were identified. In this paper we plotted the data derived from order 2 vessels, because the smaller arterioles represent the main regulation site of blood supply to capillary network (Pradhan and Chakravarthy, 2011).

Assessment of Rhythmic Diameter Changes

A computer-assisted power spectrum method, based on the generalized short time Fourier transform (GSTFT) was used to evaluate the rhythmic variations in diameter of pial arterioles (for further details see Varanini et al., 1998; Varanini, 2011; Lapi et al., 2017).

The diameter values were obtained on 30 min tracings (acquisition frequency: 4 Hz) to obtain the resolution of the six components in the following ranges: 2.5–4.5 Hz (very high frequency, VHF), 0.2–2.0 Hz (high frequency, HF), 0.06–0.2 Hz (low frequency, LF), 0.02–0.06 Hz (intermediate-low frequency, ILF), 0.0095–0.021 Hz (very low frequency, VLF), and 0.001–0.0095 Hz (ultra-low frequency, ULF) (Lapi et al., 2010).

In the protocol of single ME (Figure 1A), the data were acquired in baseline conditions, within 120–150 min and



230–260 min after ME application. In the protocol of double ME (Figure 1B), the data were acquired on tracings recorded in baseline conditions and within 110–140 min after ME2.

Data Acquisition and Statistical Analysis

All reported values are mean \pm ES. Statistical significance was set at $p < 0.05$.

For the evaluation of the arteriolar diameter changes, in single ME protocol the basal value was the average of three measurements obtained every 10 min over the 30 min of baseline conditions. Post-treatment measurements were obtained immediately after ME period and every 5 min for the whole subsequent observation period. In double ME protocol, basal value was obtained as in single ME protocol and subsequent data were obtained immediately after ME1 period, 10 min after ME1 application and immediately after ME2 period. Then, measurements were done every 5 min up to the end of the experiment. In the graphs, data were plotted every 20 min for a better graphical representation.

All data were analyzed for normal distribution with the Kolmogorov–Smirnov test. For the geometric classification of the pial arterioles in different orders, due to the normality of the data distribution, a one-way ANOVA design and the *post hoc* Bonferroni test were used. To compare the different vessel orders between hypertensive and normotensive rats in parietal and frontal regions, we used t test for unpaired data.

The changes in pial arterioles diameter and the frequency components were evaluated by one-way and two-way analysis of variance (ANOVA) for repeated measures. One-way ANOVA was applied to values derived from parietal or frontal regions, in single or double ME experimental protocols to test differences over time. Two-way ANOVA was applied to test differences between procedures (single ME vs. double ME) or brain area (parietal vs. frontal region) over time. When the ANOVA revealed a statistically significant effect ($p < 0.05$), the Bonferroni test was made for “*post hoc*” comparisons.

The statistical analysis was done by SPSS 14.0 statistical package (IBM Italia, Segrate, MI, Italy).

RESULTS

Geometric Characterization of the Pial Microvascular Network

Pial arteriolar networks in the frontal and parietal regions were classified according to vessel diameter, length and branching. Capillaries were assigned order 0 and the arterioles were assigned orders 1–5, according to their branchings.

In the parietal region, pial arterioles of hypertensive rats were organized in five orders as observed in normotensive rats (Lapi et al., 2008); in the frontal region only three orders of vessels were detected in hypertensive rats, compared to four orders of vessels recognized in normotensive animals (Table 1 and Figure 2).

By analyzing the distribution of the diameters, lengths and number of ramifications in the different orders of arterioles, we observed that the logarithm of the diameter, length and number of branches was directly proportional to the order number of the vessels (Figure 3 and Table 2). In particular, in the parietal region pial networks, the ratios, obtained as the slope of the corresponding curves, were 1.45 for the diameter, 1.23 for the

TABLE 1A | Diameter and length of each arteriolar order in baseline conditions in the parietal region of hypertensive rats.

Order	Arterioles (n)	Diameter (μm)	Length (μm)	Rats (n)
5				5
4	7	38.9 \pm 1.4*	302 \pm 128°	5
3	17	30.4 \pm 0.7*	422 \pm 69°	5
2	22	22.0 \pm 0.4*°	251 \pm 43°	5
1	30	16.1 \pm 0.3*°	175 \pm 31°	5

* $p < 0.01$ versus different order. ° $p < 0.05$ versus normotensive rats.

TABLE 1B | Diameter and length of each arteriolar order in baseline conditions in the parietal region of normotensive rats.

Order	Arterioles (n)	Diameter (μm)	Length (μm)	Rats (n)
5	4	70.1 \pm 5.9*	992 \pm 35	5
4	18	40.9 \pm 2.7*	673 \pm 21	5
3	35	32.6 \pm 1.1*	1038 \pm 59	5
2	48	23.9 \pm 0.6*	881 \pm 40	5
1	26	13.9 \pm 0.8*	299 \pm 26	5

* $p < 0.01$ versus different order.

TABLE 1C | Diameter and length of each arteriolar order in baseline conditions in the frontal region of hypertensive rats.

Order	Arterioles (n)	Diameter (μm)	Length (μm)	Rats (n)
5				5
4				5
3	11	31.5 \pm 1.4*	529 \pm 73	5
2	40	22.3 \pm 0.3*	275 \pm 30°	5
1	25	16.7 \pm 0.3*	192 \pm 28°	5

* $p < 0.01$ versus different order. ° $p < 0.05$ versus normotensive rats.

TABLE 1D | Diameter and length of each arteriolar order in baseline conditions in the frontal region of normotensive rats.

Order	Arterioles (n)	Diameter (μm)	Length (μm)	Rats (n)
5	10	58.3 \pm 3.0*	1320 \pm 42	5
4	27	41.6 \pm 2.2*	925 \pm 30	5
3	78	32.0 \pm 1.8*	480 \pm 22	5
2	113	21.7 \pm 2.0*	355 \pm 18	5
1	109	15.4 \pm 1.5*	133 \pm 12	5

* $p < 0.01$ versus different order.

length and 0.62 for the number of branchings in dexamethasone-treated rats, and were 1.07, 2.01, and 2.86, respectively, in normotensive rats. In the frontal region pial networks, the ratios for the diameter, length and number of branchings were 1.23, 1.66, and -1.53 , respectively, in dexamethasone-treated rats and were 1.08, 2.20, and 1.72, respectively, in normotensive rats (Figure 4 and Table 2).

When considering the parallel or the serial succession of the arteriolar vessels as a further characteristic of the geometric analysis of pial networks, we calculated the ratio S/E , where S was the total number of vessel segments and E was the total number of vessel elements in each given order. When this ratio was 1, a complete symmetry in bifurcations occurred, while when this ratio was greater than 1, the bifurcations were asymmetrical. As shown in Table 3, in the parietal region of dexamethasone-treated rats, the arterioles of order 4 and 1 were the most symmetrical, while those of order 3 and 2 were asymmetrical ($S/E < 1$). In normotensive rats the most symmetrical arterioles were those of order 1 and 2. In the frontal region of dexamethasone-treated rats the order 2 and 1 arterioles presented bifurcation symmetry, as observed in normotensive rats.

Effects of ME on Pial Microcirculation in Dexamethasone-Treated Rats

In the parietal region of dexamethasone-treated rats single 10 min ME caused a significant reduction in arteriolar diameter (mean diameter: 22.4 \pm 1.0 μm) with respect to the basal value [mean diameter: 25.6 \pm 1.1 μm , $F_{(15,90)} = 160.11$, $p < 0.01$] immediately after ME application (Figure 5A, gray square). Afterward, the arteriolar diameter progressively increased (mean diameter: 28.7 \pm 1.1 μm) up to 30 min after ME application. The dilation (mean diameter: 28.4 \pm 1.8 μm) became statistically significant ($p < 0.01$) (Figure 5C) and persisted for 160 min, then progressively decreased and regained the basal value at the end of the observation period (240 min, mean diameter: 26.0 \pm 1.3 μm).

In the dexamethasone-treated rats subjected to a double ME, different arteriolar diameter changes were detected (Figure 5A, black square). The significant decrement [mean diameter: 21.8 \pm 1.1 μm , $F_{(15,90)} = 160.11$, $p < 0.01$] with respect to the basal value (mean diameter: 25.6 \pm 1.1 μm), observed immediately after the first 10 min ME (ME1) application, was followed by a dilation (mean diameter: 26.3 \pm 1.1 μm) lasting up to the application of the second 10 min ME (ME2), after which a further progressive dilation occurred (Figure 5C) up to 160 min

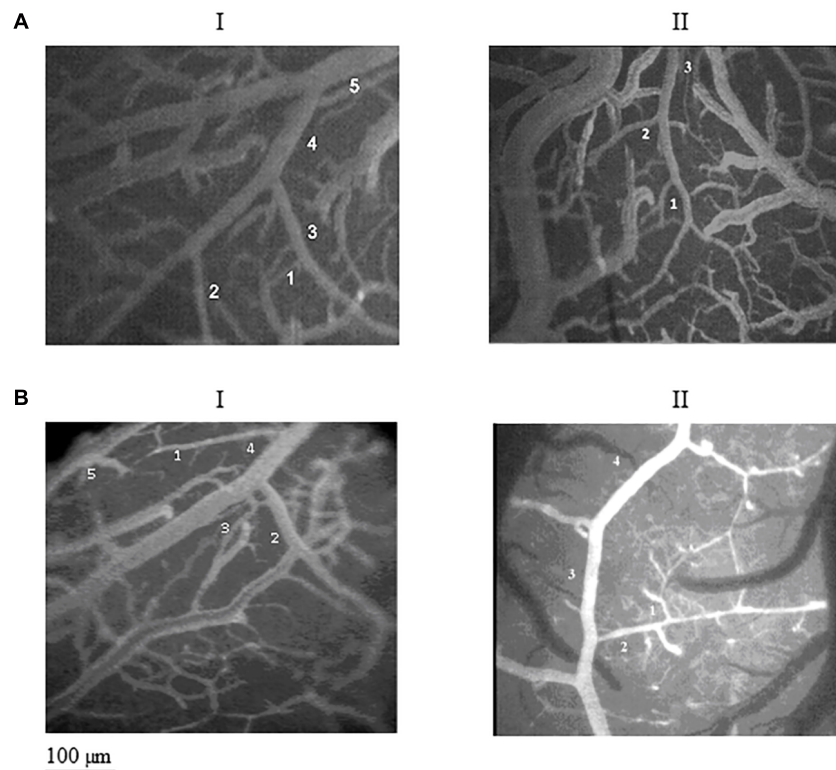


FIGURE 2 | Images of the pial microcirculation in the parietal and frontal regions of dexamethasone-treated rats (**A**) and normotensive rats (**B**). The pial arteriolar network of parietal region in the dexamethasone-treated rats (**AI**) showed five orders of vessels as well as the parietal region in normotensive rats (**BI**). The pial arteriolar network of frontal region in the dexamethasone-treated rats (**AII**) showed only three orders of vessels, while in the frontal region of normotensive rats (**BII**) four orders of vessels have been observed.

after ME2, reaching a statistically significant value with respect to both basal value and the value recorded after ME1 (mean diameter: $29.2 \pm 1.2 \mu\text{m}$, $p < 0.01$ vs. basal value, $p < 0.05$ vs. 10 min after ME1). Interestingly, the comparison between the two treatments (single vs. double ME, # in the **Figure 5A**) showed a significant difference after 180 min after ME2 [$F_{(15,90)} = 48.51$, $p < 0.05$] indicating that the double treatment prolonged the vasodilative effect.

In the frontal region, in the dexamethasone-treated rats subjected to single 10 min ME, the pial arterioles did not show any statistically significant diameter changes (**Figure 5B**, gray rhombus), although a trend of dilation was observed between 20 and 160 min after ME application (**Figure 5D**). In the dexamethasone-treated rats subjected to double ME, the pial arterioles showed no changes in diameters after ME1 and after ME2 up to 60 min (**Figure 5B**, black rhombus). Starting from 80 min after ME2, a progressive statistically significant dilation occurred (**Figure 5D**) up to 180 min after ME2 [**Figure 5B**, black rhombus; mean diameter: $30.5 \pm 0.5 \mu\text{m}$, $F_{(15,90)} = 41.85$, $p < 0.05$ vs. basal value $25.1 \pm 0.5 \mu\text{m}$, $p < 0.01$ vs. 10 min after ME1 $24.90 \pm 0.59 \mu\text{m}$]. This dilation was maintained for the subsequent observation period (up to 240 min after ME2), thus outlining a significant difference between single ME treatment starting from 160 min after ME2 [# in **Figure 5B**, $F_{(15,90)} = 48.00$, $p < 0.01$].

Since the pial arterioles of the frontal region showed a different trend of the diameter changes compared to that recorded in the parietal area, we studied dexamethasone-treated rats ($n = 3$) subjected to double MEs, in which two cranial windows were simultaneously implanted in the frontal and parietal levels, to exclude that the observed differences were attributable to the belonging to different animals. As shown in **Figure 6**, in both parietal and frontal regions no difference was detected in the responses of the pial arterioles with respect to those observed in the dexamethasone-treated rats with a single cranial window implanted in parietal or in frontal region.

Finally, the SO dexamethasone-treated rats did not show any change in the arteriolar diameter, except for the physiological vasomotion (**Figure 7**).

Effects of ME on Rhythmic Oscillations of the Diameter in Pial Arterioles of Dexamethasone-Treated Rats

In all animals utilized, during the vasodilation induced by ME, modifications of the arteriolar diameter rhythmic oscillations were observed in both the parietal and frontal region.

In the dexamethasone-treated rats subjected to single ME, the spectral analysis of pial arteriolar rhythmic diameter changes, performed in the parietal region on recordings carried out

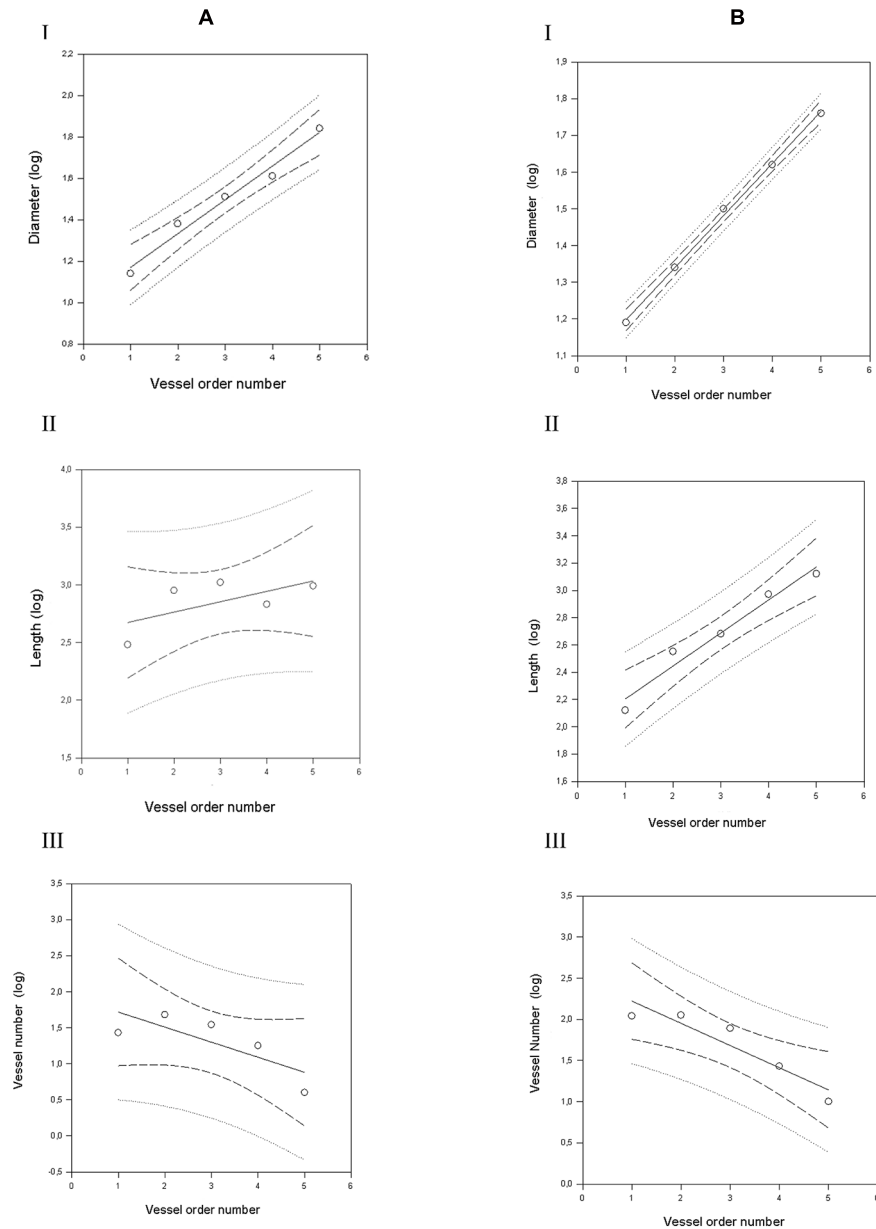


FIGURE 3 | Geometric characterization of the pial arterioles in parietal cortex in dexamethasone-treated rats **(A)** and normotensive rats **(B)**. **(A)** The relationships between the logarithm of diameter **(I)**, length **(II)**, and vessel element number **(III)** in the successive orders of vessels were calculated for the pial arterioles in the dexamethasone-treated rats. **(B)** The relationships between the logarithm of diameter **(I)**, length **(II)**, and vessel element number **(III)** in the successive orders of vessels were calculated for the pial arterioles in the normotensive rats. The dashed lines delimit the confidence intervals.

between 130 and 160 min after ME, showed significant changes of the frequency components. In particular, there was an increase in the spectral density of endothelial ULF [$F_{(2,12)} = 5929.01$, $p < 0.01$], VLF [$F_{(2,12)} = 2416.67$, $p < 0.01$], neurogenic [ILF, $F_{(2,12)} = 314.33$, $p < 0.01$], and myogenic activity [LF, $F_{(2,12)} = 259.62$, $p < 0.01$]. On the other hand, there was a significant decrease of the frequency components associated to the respiration and the heart rates (HF and VHF) after ME compared with baseline conditions [$F_{(2,12)} = 754.92$, $p < 0.01$ and $F_{(2,12)} = 482.97$, $p < 0.01$, respectively] (**Figures 8A1,A2**).

After 160 min from ME the arteriolar diameter progressively decreased and the frequency components recorded between 230 and 260 min recovered the basal values (**Figure 8A3**).

The same analysis carried out in the pial arterioles belonging to the frontal region showed (between 120 and 150 min) a significant increase in spectral density of ULF, VLF, ILF, and LF [$F_{(2,12)} = 241.28$, $p < 0.01$, $F_{(2,12)} = 296.94$, $p < 0.01$ and $F_{(2,12)} = 125.09$, $p < 0.01$, $F_{(2,12)} = 91.77$, $p < 0.01$, respectively] (**Figures 8B1,B2**) and a significant decrease of HF [$F_{(2,12)} = 578.44$, $p < 0.01$] and VHF [$F_{(2,12)} = 36.23$, $p < 0.01$]

TABLE 2A | Empirical constants a and b of equations 1, 2, and 3 for semilogarithmic relationships between mean diameter, length, number of vessel elements and order number of arterioles in the parietal region of hypertensive rats.

	Equation		
	(1) Diameter $\log_{10}Dn = a + bn$	(2) Length $\log_{10}Ln = a + bn$	(3) Arteriolar number $\log_{10}Nn = a + bn$
a	1.007	2.584	1.927
b	0.163	0.090	-0.209
R^2	0.097	0.414	0.614
Ratio	1.45	1.23	-0.62

Data derived from 5 animals. Ratio is that between successive orders.
 R^2 = Correlation coefficient; n = number of vessel elements.

TABLE 2B | Empirical constants a and b of equations 1, 2, and 3 for semilogarithmic relationships between mean diameter, length, number of vessel elements and order number of arterioles in the parietal region of normotensive rats.

	Equation		
	(1) Diameter $\log_{10}Dn = a + bn$	(2) Length $\log_{10}Ln = a + bn$	(3) Arteriolar number $\log_{10}Nn = a + bn$
a	1.070	2.011	2.857
b	0.145	0.240	-0.360
R^2	0.995	0.998	0.966
Ratio	1.41	1.75	2.08

Data derived from 5 animals. Ratio is that between successive orders.
 R^2 = Correlation coefficient; n = number of vessel elements.

TABLE 2C | Empirical constants a and b of equations 1, 2, and 3 for semilogarithmic relationships between mean diameter, length, number of vessel elements and order number of arterioles in the frontal region of hypertensive rats.

	Equation		
	(1) Diameter $\log_{10}Dn = a + bn$	(2) Length $\log_{10}Ln = a + bn$	(3) Arteriolar number $\log_{10}Nn = a + bn$
a	1.098	2.040	1.720
b	0.135	0.220	-0.185
R^2	0.996	0.976	0.422
Ratio	1.36	1.66	-1.53

Data derived from 5 animals. Ratio is that between successive orders.
 R^2 = Correlation coefficient; n = number of vessel elements.

TABLE 2D | Empirical constants a and b of equations 1, 2, and 3 for semilogarithmic relationships between mean diameter, length, number of vessel elements and order number of arterioles in the frontal region of normotensive rats.

	Equation		
	(1) Diameter $\log_{10}Dn = a + bn$	(2) Length $\log_{10}Ln = a + bn$	(3) Arteriolar number $\log_{10}Nn = a + bn$
a	1.085	2.200	1.725
b	0.128	0.095	-0.200
R^2	0.998	0.569	0.914
Ratio	1.34	1.24	-0.63

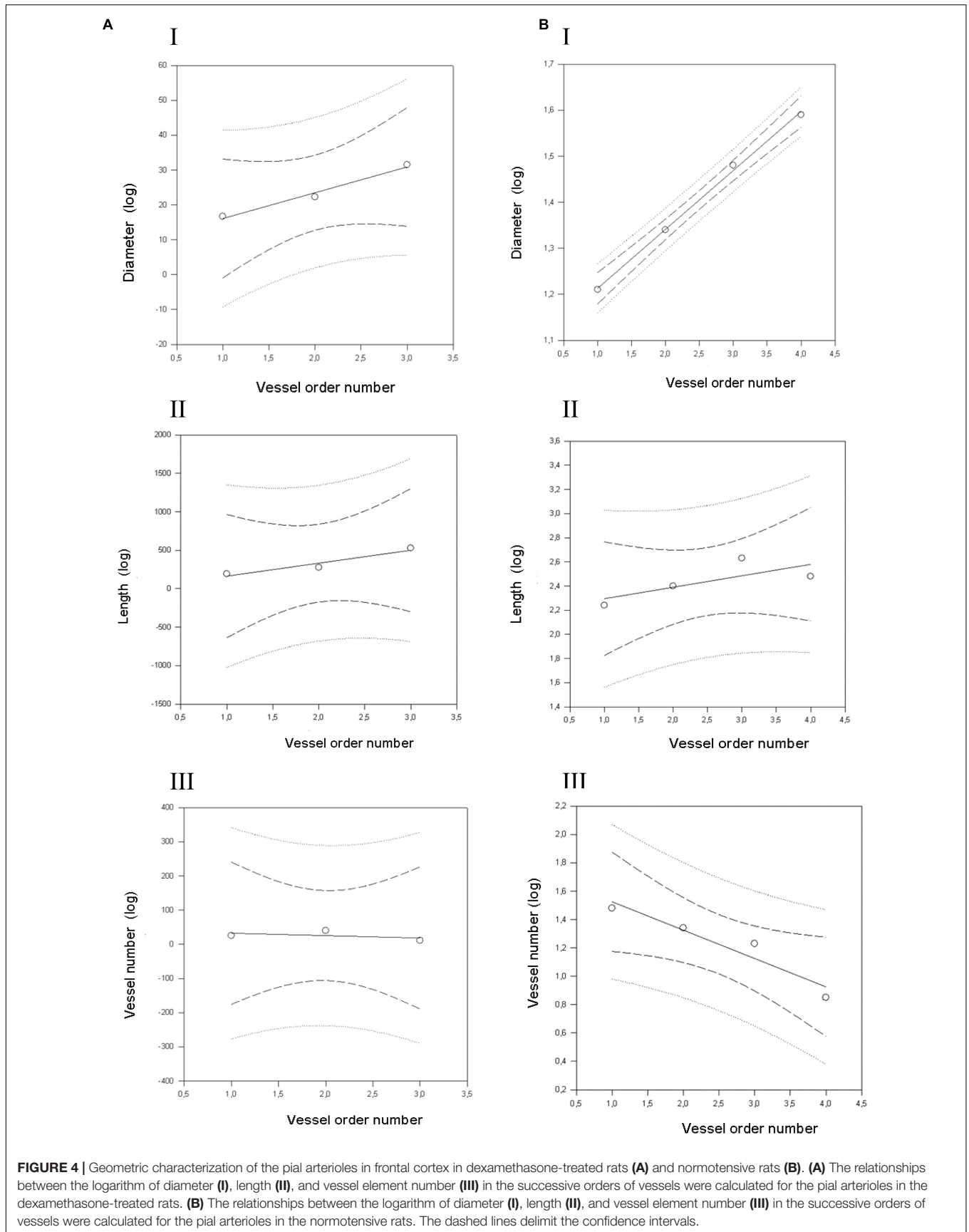
Data derived from 5 animals. Ratio is that between successive orders.
 R^2 = Correlation coefficient; n = number of vessel element.

compared with baseline conditions. All frequency components recovered the basal values between 230 and 260 min after ME (**Figure 8B3**). Interestingly, the spectral density pattern obtained in frontal region pial arterioles resulted significantly different compared to the one outlined in parietal region (# in **Figure 8**).

In the dexamethasone-treated rats subjected to double ME, at 110–140 min, pial arterioles in the parietal regions showed a significant increase in spectral density of ULF, VLF, ILF, and LF frequency components with respect to baseline conditions (**Figure 9-1,2**) [$F_{(2,12)} = 296.05$, $p < 0.01$, $F_{(2,12)} = 1809.52$, $p < 0.01$, $F_{(2,13)} = 360.34$, $p < 0.01$, and $F_{(2,12)} = 121.37$, $p < 0.01$, respectively] and with respect to the same period (130–160 min) after the single ME [$F_{(1,9)} = 231.92$, $p < 0.01$, $F_{(1,9)} = 120.68$, $p < 0.01$, $F_{(1,8)} = 238.78$, $p < 0.01$ and $F_{(1,9)} = 358.62$, $p < 0.01$, respectively]. HF and VHF components, instead, showed a significant decrease in spectral density after ME2 with respect to the baseline conditions [$F_{(2,12)} = 2077.74$, $p < 0.01$ and $F_{(2,12)} = 775.23$, $p < 0.01$, respectively] and with respect to the same period (130–160 min) after the single ME [$F_{(1,9)} = 858.29$, $p < 0.01$, $F_{(1,9)} = 2873.68$, $p < 0.01$]. The same pattern was detected in the recordings at 210–240 min after ME2 (**Figure 9-3**), thus resulting that there was no recovery of the baseline conditions, when compared to single ME.

A similar pattern was observed for the pial arterioles in the frontal region. At 110–140 min after ME2, ULF, VLF, and ILF frequency components showed a significant increase in spectral density compared to baseline conditions [$F_{(2,12)} = 311.48$, $p < 0.01$, $F_{(2,12)} = 1939.70$, $p < 0.01$ and $F_{(2,12)} = 156.96$, $p < 0.01$, respectively] (**Figure 10-1,2**) and with respect to the same period (130–160 min) after the single ME [$F_{(1,9)} = 614.42$, $p < 0.01$, $F_{(1,9)} = 14080.24$, $p < 0.01$, and $F_{(1,9)} = 392.27$, $p < 0.01$, respectively]. The LF frequency component increased in spectral density with respect to the baseline conditions [$F_{(2,12)} = 834.15$, $p < 0.01$] but not with respect to the same period (130–160 min) after the single ME [$F_{(1,9)} = 1.29$, $p = 0.29$]. HF and VHF frequency components, on the contrary, significantly decreased in spectral density [$F_{(2,12)} = 877.43$, $p < 0.01$ and $F_{(2,12)} = 344.50$, $p < 0.01$, respectively]. The baseline conditions did not recover, indeed, at 210–240 min after ME2 (**Figure 10-3**), and we detected values similar to those obtained at 110–140 min.

Also in this case, the pattern of the power spectral density obtained in frontal region was significantly different from that obtained in parietal region (# in **Figure 10**). In particular, the statistical analysis revealed that ULF, VLF, and ILF were reduced in all times considered [ULF: $F_{(1,9)} = 191.11$, $p < 0.01$, $F_{(1,9)} = 369.38$, $p < 0.01$ and $F_{(1,9)} = 80.37$, $p < 0.01$, for baseline conditions, at 110–140 min after ME2 and at 210–240 min after ME2, respectively; VLF: $F_{(1,9)} = 722.00$, $p < 0.01$, $F_{(1,9)} = 490.84$, $p < 0.01$ and $F_{(1,9)} = 756.53$, $p < 0.01$, for baseline conditions, at 110–140 min after ME2 and at 210–240 min after ME2, respectively; ILF: $F_{(1,9)} = 288.33$, $p < 0.01$, $F_{(1,9)} = 3342.01$, $p < 0.01$ and $F_{(1,9)} = 195.48$, $p < 0.01$, for baseline conditions, at 110–140 min after ME2 and at 210–240 min after ME2, respectively], while LF component was increased [$F_{(1,9)} = 225.63$, $p < 0.01$, $F_{(1,9)} = 827.01$, $p < 0.01$ and $F_{(1,9)} = 623.18$, $p < 0.01$,



for baseline conditions, at 110–140 min after ME2 and at 210–240 min after ME2, respectively].

In the SO dexamethasone-treated rats, no changes in all frequency components were detected for the whole observation period. Interestingly, as shown in **Figure 11**, the distribution of the frequency components indicated that ULF, VLF, and ILF components were significantly lower in frontal region

[ULF: $F_{(1,9)} = 1251.27, p < 0.01$ and $F_{(1,9)} = 775.76, p < 0.01$ for baseline conditions and at 120–150 min, respectively; VLF: $F_{(1,9)} = 1020.60, p < 0.01$ and $F_{(1,9)} = 700.41, p < 0.01$ for baseline conditions and at 120–150 min, respectively; ILF: $F_{(1,9)} = 269.08, p < 0.01$ and $F_{(1,9)} = 56.76, p < 0.01$ for baseline conditions and at 120–150 min, respectively]; while LF was significantly higher with respect to the parietal region [$F_{(1,9)} = 160.51, p < 0.01$ and $F_{(1,9)} = 366.51, p < 0.01$, for baseline conditions, at 120–150 min, respectively].

In all animals utilized, for the whole observation period mean arteriolar blood pressure (MABP) and heart rate (HR) were recorded. Single ME induced a significant reduction of MABP and HR, with MABP that recovered the basal value after 120 min, while HR persistently reduced for the subsequent observation period. In the experiment with double ME, ME2 caused a marked reduction of MABP (about 30 mmHg) lasting for the whole observation period (about 4 h), and a slight decrease of HR. These data are reported in Del Seppia et al. (2018).

TABLE 3A | Ratio of the total number of elements in each vessels order (S/E) in the parietal region of hypertensive rats.

Order	S/E	N
1	1.10	27
2	0.81	48
3	0.60	35
4	1.40	18
5	3.00	4

Values are means \pm SE.

N, number of vessels observed for each order.

TABLE 3B | Ratio of the total number of elements in each vessels order (S/E) in the parietal region of normotensive rats.

Order	S/E	N
1	1.03	30
2	1.35	43
3	1.79	38
4	3.36	22
5	2.78	5

Values are means \pm SE.

N, number of vessels observed for each order.

TABLE 3C | Ratio of the total number of elements in each vessels order (S/E) in the frontal region of hypertensive rats.

Order	S/E	N
1	1.20	25
2	1.80	40
3	2.50	11
4		
5		

Values are means \pm SE.

N, number of vessels observed for each order.

TABLE 3D | Ratio of the total number of elements in each vessels order (S/E) in the frontal region of normotensive rats.

Order	S/E	N
1	1.10	30
2	1.54	22
3	1.82	17
4	1.57	7
5		

Values are means \pm SE.

N, number of vessels observed for each order.

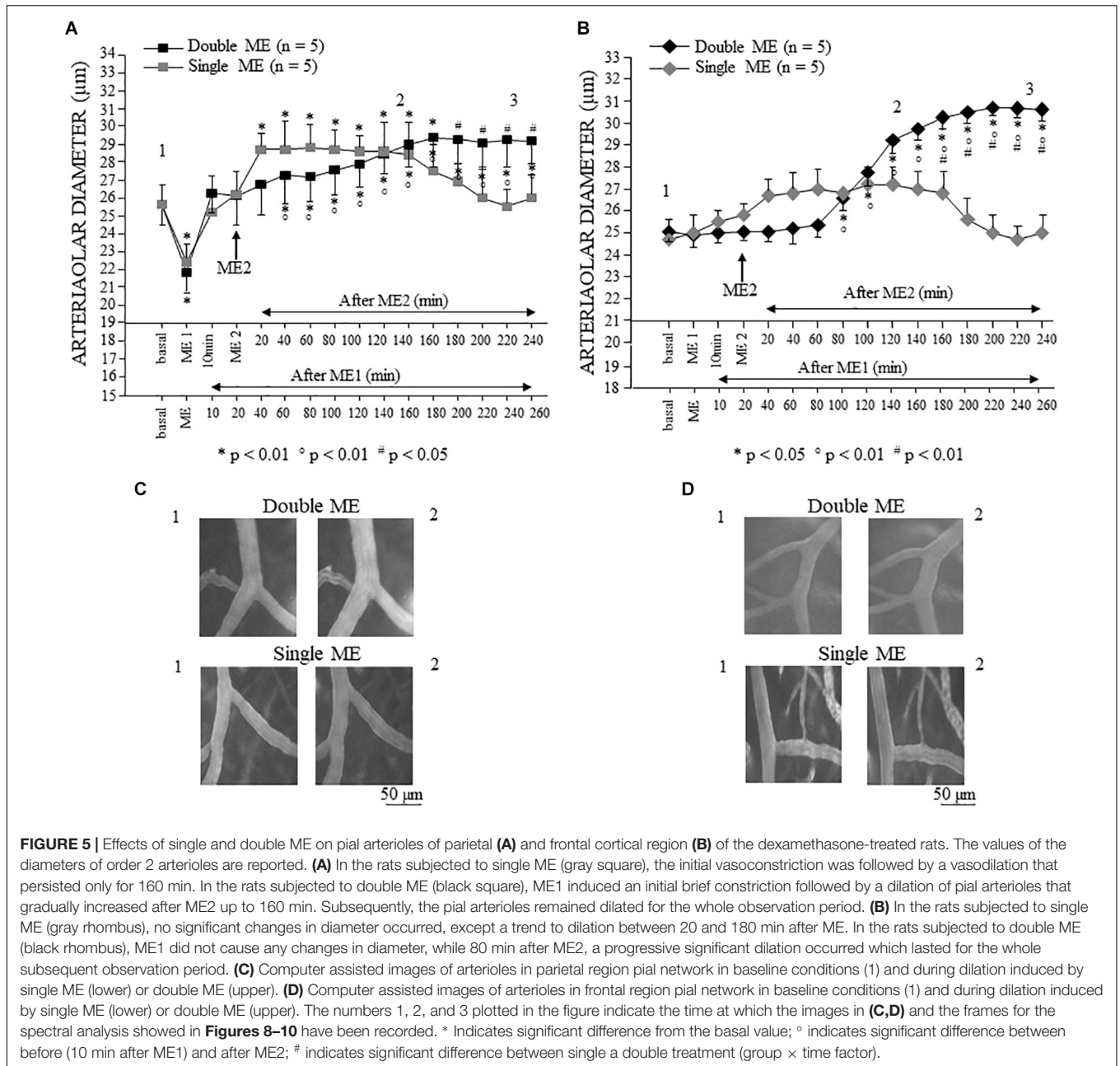
DISCUSSION

Previously, we described that repeated MEs in normotensive rats markedly prolonged the long-lasting dilation of pial arterioles produced by single ME, promoting a change in the regulation of their diameters (Lapi et al., 2017). In this paper we extended our observation in rats presenting experimental hypertension induced by treatment with dexamethasone. The study was carried out on pial arterioles in the parietal and frontal regions of the brain, being the first area involved in the elaboration of the trigeminal input responsible of the ME effects (Lapi et al., 2013), and the latter area, taken as a control area, not directly involved in the trigeminal processing. We tried to evaluate whether the effects induced by ME on the pial microcirculation were exclusively due to trigeminal afferents elaborations or were also due, partly or totally, to systemic effects involving all the brain areas.

As a first step, we provided, for the first time, the geometric characterization of the pial arteriolar networks in dexamethasone-treated rats.

By applying the Strahler's method, which allowed us to identify the different orders of vessels (Kassab et al., 1993), we found five orders of vessels in the parietal region of the dexamethasone-treated rats as occurs in normotensive rats (Lapi et al., 2008), while in the frontal region there were three orders of vessels in the dexamethasone-treated rats and four in normotensive rats. Moreover, the number of vessels for each order was higher in normotensive than in dexamethasone-treated rats.

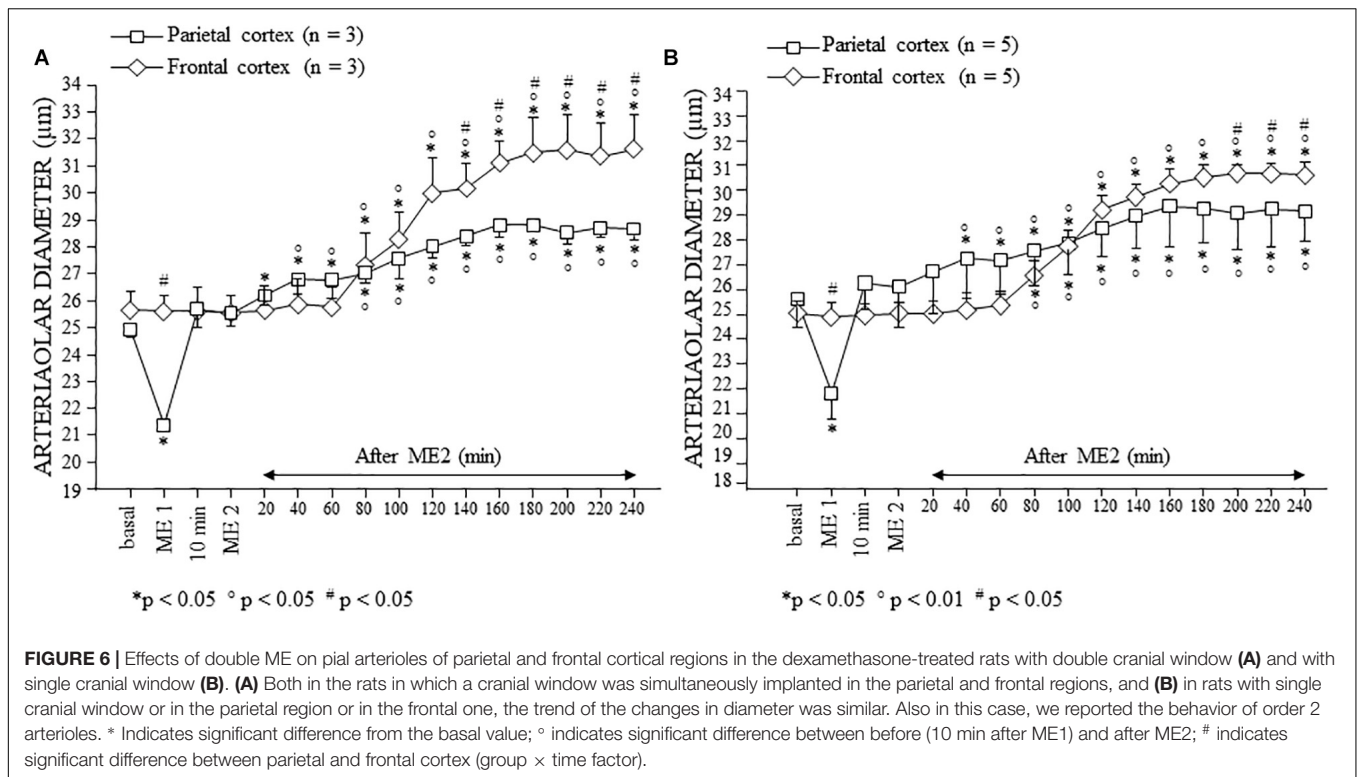
Subsequently, we verified that the arteriolar diameter, length and number of the ramifications followed the Horton's law and therefore, the arteriolar networks resulted to have a fractal distribution. In fact, in the parietal region of both dexamethasone-treated rats and normotensive rats the diameter, length and number of ramifications grew as the order number grew. A fractal distribution was present also in the frontal region of the normotensive rats, as well as in the dexamethasone-treated rats, where the number of ramifications decreased. Another assessed parameter was the segments/elements ratio that



indicates the symmetry of the arteriolar bifurcations. This feature is important to evaluate an adequate blood flow distribution in the capillary networks. We observed that the highest order vessels had more asymmetric bifurcations both in the parietal and frontal regions, both in dexamethasone-treated rats and in normotensive rats. Therefore, the detected reduced number of arterioles and the greater asymmetry in the ramifications confirm in dexamethasone-treated rats what has already been demonstrated in previous experimental works on animal models (Baumbach and Heistad, 1989, 1991) and humans (Pires et al., 2013), i.e., hypertension causes a marked arteriolar rarefaction of the cerebral circulation.

The second part of our work has concerned the effects of a double ME compared with a single ME on the dexamethasone-treated rat pial circulation. In previous studies conducted in our laboratory, single or double ME were tested in normotensive rats detecting a strong reduction in MABP and a particular modulation of arteriolar tone in the parietal area (Lapi et al., 2017).

In dexamethasone-treated rats, we observed that, when no ME was applied, the vessels diameter showed only the physiological rhythmic changes during the whole observation period of 300 min in both parietal and frontal region (Figure 7). In the parietal region, when a single 10 min ME was applied,



a vasoconstriction immediately followed by a vasodilation occurred, which approached its nadir 120 min after ME and then gradually regained basal values. This response is similar to that previously observed by us in normotensive rats with regard to its time-course, however, smaller in terms of amplitude (22% increase of arteriolar diameter in parietal region pial networks in normotensive rats, and 12,5% increase in parietal region pial networks in dexamethasone-treated rats, Lapi et al., 2017). On the contrary, in the frontal region, only a trend to arteriolar dilation that did not reach the statistical significance

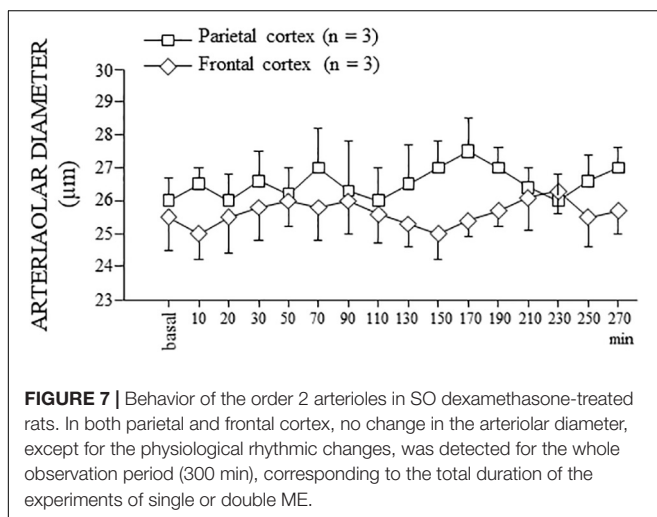
was observed between 20 and 160 min after ME application (Figure 5B).

Our results further demonstrate that arteriolar dilation was greatly enhanced, in terms of amplitude and duration, when ME was repeated. In fact, while single ME, in the parietal region, induced arteriolar dilation (about 3 μm) that ended in about 2 h, and in the frontal region no statistically significant increase of the vessels diameters occurred, double MEs were followed by a diameters increase (about 4 μm), in the parietal area, and in frontal area (about 5 μm), that lasted for the entire subsequent observation period (Figure 5).

In parietal region arteriolar networks, the response to double ME has similar time-course to that previously observed by us in normotensive rats. However, it was smaller in terms of amplitude (24% increase in normotensive rats, Lapi et al., 2017, 15% in dexamethasone-treated rats).

It is worth noting that, in the frontal region, the second ME was necessary for arteriolar dilation, since single ME was not able to induce a significant change in the arteriolar diameter. A possible explanation is that this response was modulated by hypertension that determines a lower responsiveness of vascular smooth muscle cells to nitric oxide released by endothelial cells (Shesely et al., 1996; Paton et al., 2007; Zhu et al., 2016). Therefore, the second ME seems to be necessary to increase NO release from the endothelium activated by the first ME (Lapi et al., 2017): a greater amount of NO may facilitate arteriolar dilation.

Moreover, in the frontal region, no vasoconstriction was detected during ME. This is in agreement with what has



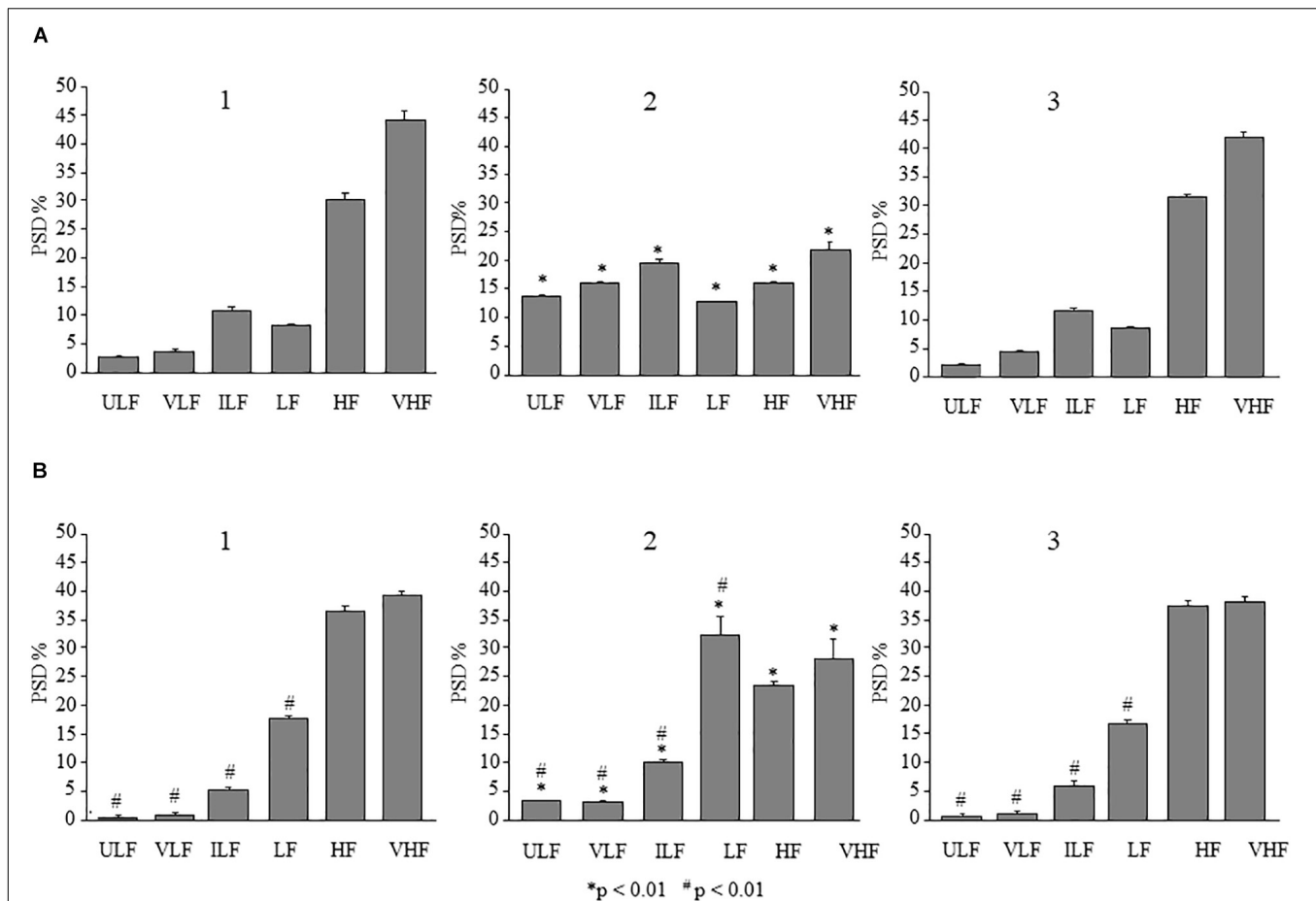
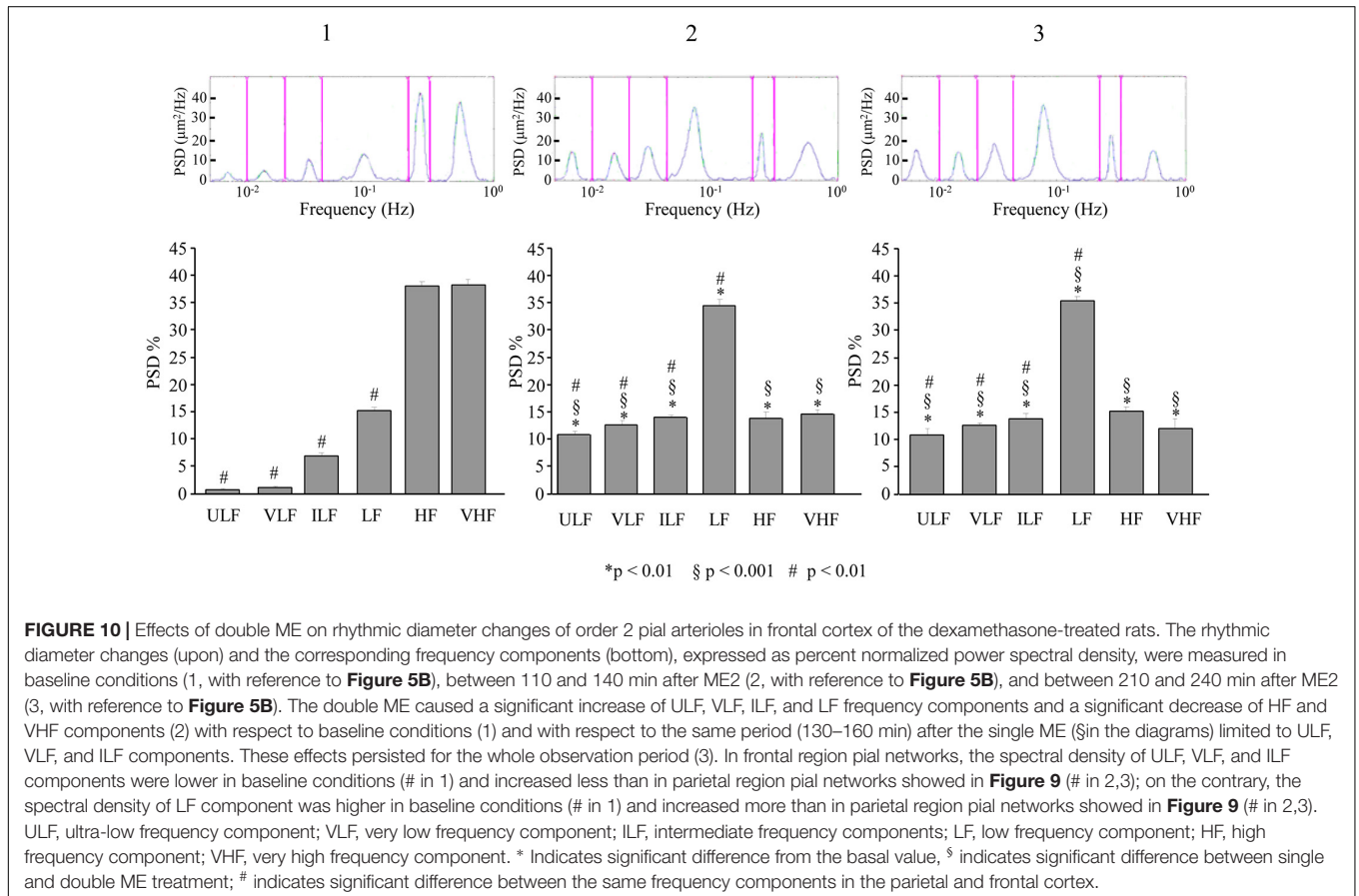
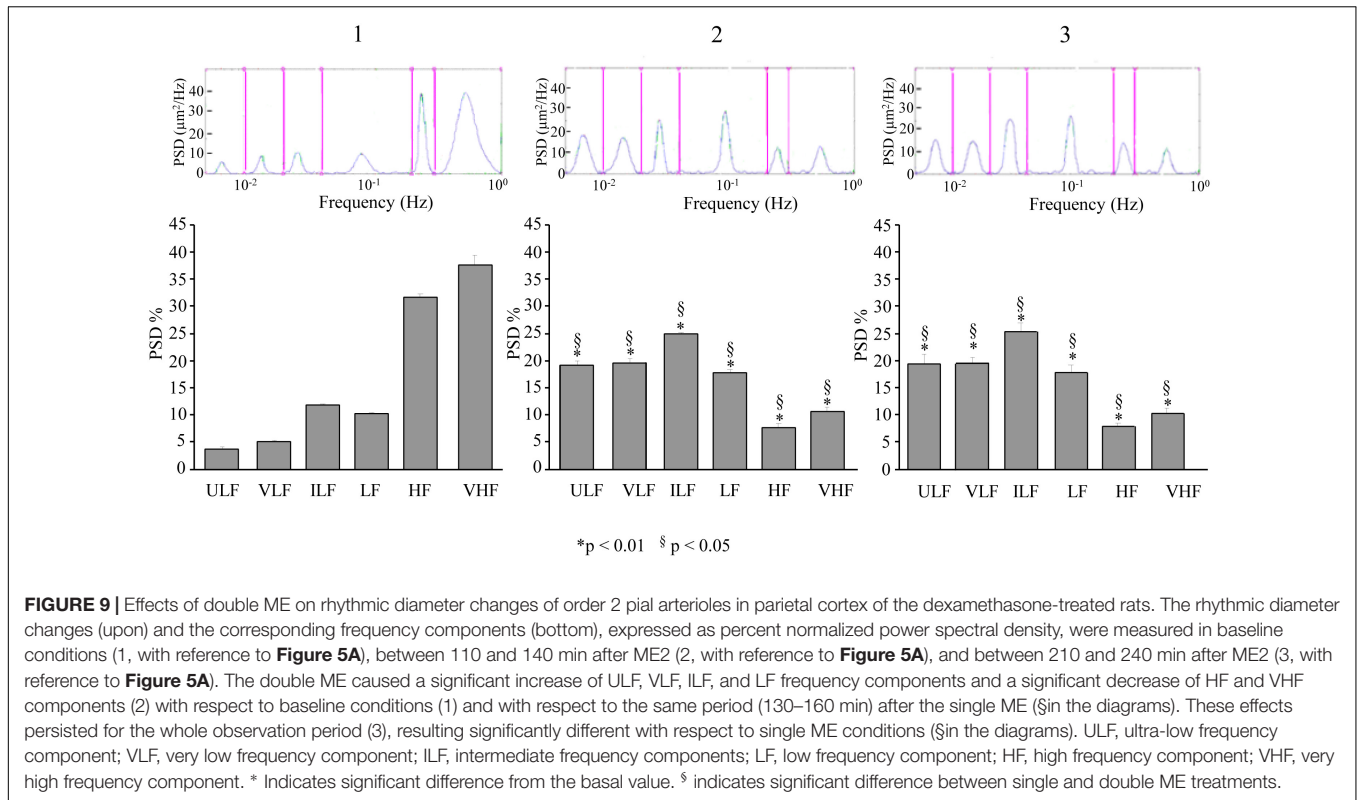


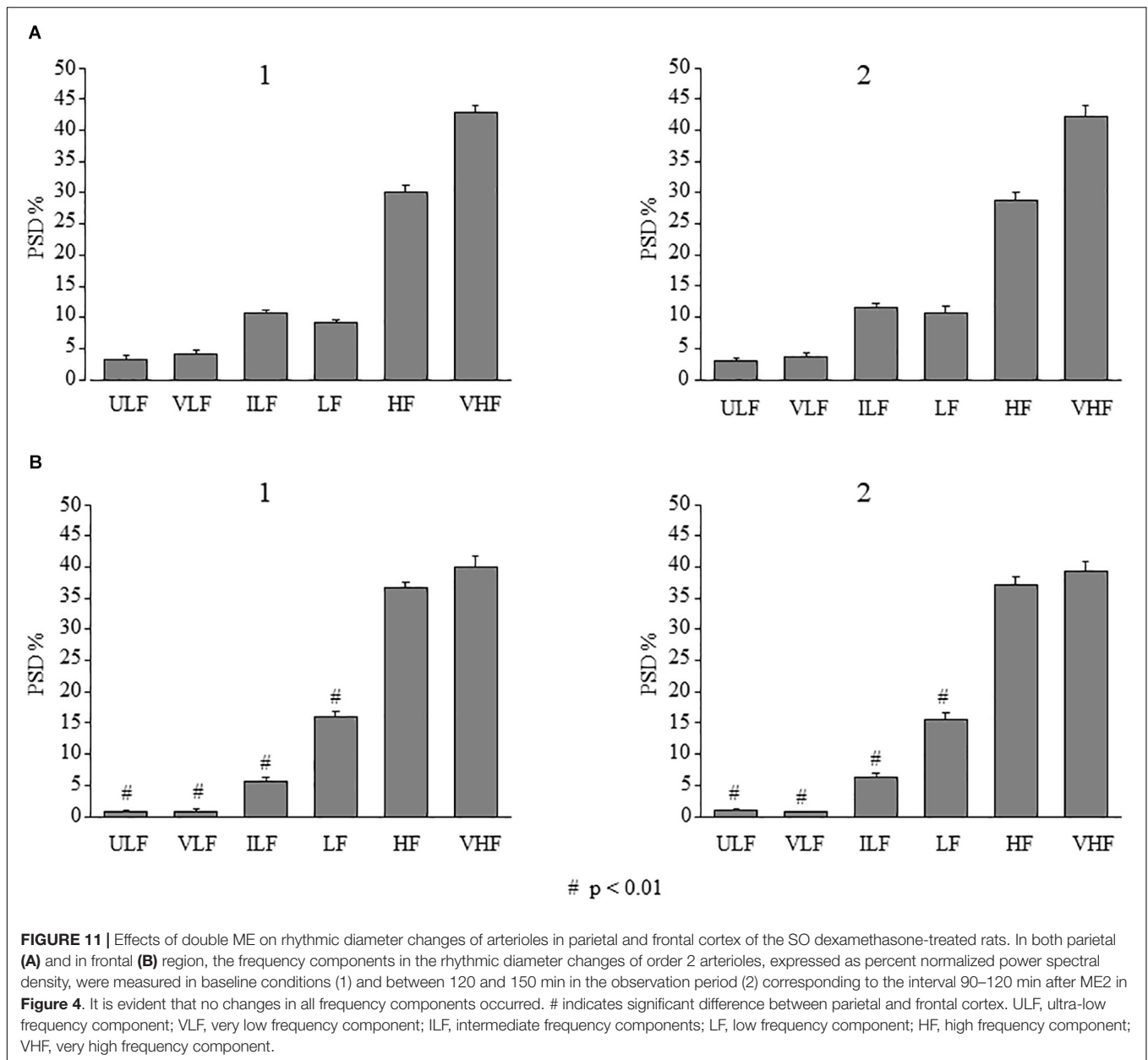
FIGURE 8 | Comparison between the effects of single ME on rhythmic diameter changes in parietal and frontal cortex of the dexamethasone-treated rats. The frequency components in the rhythmic diameter changes of order 2 arterioles, expressed as percent normalized power spectral density, were measured in baseline conditions (1), at the pick of the vasodilation with recordings between 130 and 160 min after ME (2), and during the recovery of the baseline conditions with recordings between 230 and 260 min after ME (3). **(A)** In the parietal region, ME caused a significant increase of the ULF, VLF, ILF, and LF frequency components and a decrease of HF and VHF components **(A2)** compared with the baseline conditions **(A1)**; afterwards all frequency components recovered the basal values **(A3)**. **(B)** Also in the frontal region, ME caused a significant increase of the ULF, VLF, ILF, and LF frequency components and a decrease of HF and VHF components **(B2)** compared with the baseline conditions **(B1)**, which have been recovered between 230 and 260 min after ME **(B3)**. ULF, ultra-low frequency component; VLF, very low frequency component; ILF, intermediate frequency components; LF, low frequency component; HF, high frequency component; VHF, very high frequency component. *Indicates significant difference from the basal value; # indicates significant difference between parietal and frontal cortex.

been previously observed in normotensive rats (Lapi et al., 2014), where ME-induced arteriolar constriction was abolished by inhibition of the nociceptors. Therefore, in the frontal region the signals from nociceptors are reduced compared to the parietal region where the information brought by the trigeminal afferents is processed and neuron activation affects the arteriolar tone. On the other hand, affecting the cerebral circulation in a widespread way, the vasodilatory effect seems to depend on influences that the trigeminal stimulation can elicit on NO release mechanisms. Previous data demonstrated that pial arteriolar dilation was inhibited by NOS inhibition in normotensive rats. The decrease in systemic blood pressure and changes in heart rate may be related to the involvement of vasomotor and vagal centers, as previously suggested (Lapi et al., 2014). Moreover, recent work has indeed

demonstrated that neurotransmitters and neuromodulators, such as glutamate and ATP, stimulate NO release by inducing endothelial Ca^{2+} signals (Guerra et al., 2018; Zuccolo et al., 2018). Moreover, this Ca^{2+} signal could recruit EDH. Hypertension may alter the endothelial Ca^{2+} machinery, thereby affecting endothelial-dependent vasodilation (Nistri et al., 2012; Seki et al., 2017).

Finally, as reported in several studies, arterial hypertension is associated with morphologic and functional alterations of the endothelium, such as increases in endothelial cell volume (Vogt and Schmid-Schönbein, 2001), extracellular matrix (Lemarié et al., 2010) and vascular responsiveness to vasoconstrictor stimuli (Rajagopalan et al., 1996). In hypertensive animals, there is evidence that endothelium-dependent relaxation is impaired, probably due to a reduced release of endothelium-derived





relaxing factor or nitric oxide (Furchgott and Vanhoutte, 1989). Our analysis of the rhythmic diameter changes in pial arterioles showed that ME determined a characteristic modulation of oscillatory frequency components.

We observed that in dexamethasone-treated rats the endothelial components (ULF and VLF) were reduced compared with those observed in normotensive rats (Lapi et al., 2017). Moreover, in frontal region pial arterioles, these components were poorly represented with respect to the parietal region. The application of single ME caused a significant increase in the frequency components related to endothelial (ULF and VLF), neurogenic (ILF) and myogenic (LF) activity in the parietal and frontal regions. This effect disappeared when the diameter of the pial arterioles regained basal values. Double ME, in the parietal

region, induced a marked increase of the ULF, VLF, ILF, and LF components compared with baseline conditions; this increase was also observed in the frontal region even if less pronounced. In both brain cortical areas it lasted for the entire observation period (4 h).

Therefore, it seems conceivable to suggest that arteriolar dilation was induced by mechanisms facilitating the release of NO, stimulated by ME and overstimulated by double ME.

In conclusion, for the first time, we observed that ME repetition markedly prolongs the dilation of pial arterioles induced by single ME, in a model of experimentally induced hypertension, in which a reorganization of the microvascular brain system occurs, especially in the frontal area where than

pial arterioles have few asymmetrical ramifications causing alteration of the perfusion of the capillaries. Moreover, the application of a non-invasive procedure such as ME determines reactivation of the endothelium function impaired by arterial hypertension, as indicated by a shift toward increased spectral density of the high frequency components. The mechanisms underlying these effects need to be clarified and further experiments are in progress.

However, this experimental model of hypertension allowed us to evaluate several important effects of trigeminal nerve stimulation that could be a first approach to test this procedure even in hypertensive subjects.

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AUTHOR CONTRIBUTIONS

DL, AC, and RS conceived the project. DL, GF, LG, and MV performed the experiments. CDS, AC, and RS contributed to discussions regarding the project. MDM analyzed the geometric features of pial arterioles. DL and RS analyzed the data, wrote and revised the manuscript.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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