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► **To cite this version:**

N. L Lilli, L. Quénéhervé, S. Haddara, C. Brochard, P. Aubert, et al.. Glioplasticity in irritable bowel syndrome. *Neurogastroenterology & Motility*, 2018, 30 (4), pp.e13232. 10.1111/nmo.13232 . hal-03153591

HAL Id: hal-03153591

<https://cnrs.hal.science/hal-03153591>

Submitted on 9 Mar 2021

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Glioplasticity in irritable bowel syndrome

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Funding information

Part of study was funded by an Almirall grant 'Defining IBS-C as a gliopathy' and a grant from Region Pays de la Loire (Vacarme).

Abbreviations: 7-AAD, 7-aminoactinomycin D; ATP, adenosine triphosphate; DMEM, Dulbecco's modified Eagle medium; EGC, enteric glial cells; ENS, enteric nervous system; HC, healthy control; H1R, histamine H1 receptor; IBS, irritable bowel syndrome; IBS-C, constipation-predominant IBS; IBS-D, diarrhea-predominant IBS; IBS-M, mixed-IBS; qPCR, quantitative PCR.

Abstract

Background: Growing evidence indicates a wide array of cellular remodeling in the mucosal microenvironment during irritable bowel syndrome (IBS), which possibly contributes to pathophysiology and symptom generation. Here, we investigated whether enteric glial cells (EGC) may be altered, and which factors/mechanisms lead to these changes.

Methods: Colonic mucosal biopsies of IBS patients (13 IBS-Constipation [IBS-C]; 10 IBS-Diarrhea [IBS-D]; 11 IBS-Mixed [IBS-M]) and 24 healthy controls (HC) were analyzed. Expression of S100 β and GFAP was measured. Cultured rat EGC were incubated with supernatants from mucosal biopsies, then proliferation and Ca²⁺ response to ATP were analyzed using flow cytometry and Ca²⁺ imaging. Histamine and histamine 1-receptor (H1R) involvement in the effects of supernatant upon EGC was analyzed.

Key Results: Compared to HC, the mucosal area immunoreactive for S100 β was significantly reduced in biopsies of IBS patients, independently of the IBS subtype. IBS-C supernatants reduced EGC proliferation and IBS-D and IBS-M supernatants reduced Ca²⁺ response to ATP in EGC. EGC expressed H1R and the effects of supernatant upon Ca²⁺ response to ATP in EGC were blocked by pyrilamine and reproduced by histamine via H1R. IBS supernatants reduced mRNA expression of connexin-43. The S100 β -stained area was negatively correlated with the frequency and intensity of pain and bloating.

Conclusion and Inferences: Changes in EGC occur in IBS, involving mucosal soluble factors. Histamine, via activation of H1R-dependent pathways, partly mediates altered Ca²⁺ response to ATP in EGC. These changes may contribute to the pathophysiology and the perception of pain and bloating in patients with IBS.

KEYWORDS

Ca²⁺ response, enteric glial cells, histamine, irritable bowel syndrome

1 | INTRODUCTION

Irritable bowel syndrome (IBS) is a functional intestinal disease characterized by chronic abdominal pain and altered bowel habits with a world prevalence of about 10%-25% worldwide.¹ Subtypes of IBS have been defined according to bowel habit patterns, including IBS with predominant constipation (IBS-C), predominant diarrhea (IBS-D), mixed bowel habits (IBS-M), and 'unclassified' (IBS-U) in patients who do not meet diagnostic criteria for IBS-C, D, or M.² Although the etiology of IBS remains unknown, major advances have been achieved over the past few years enabling a better pathophysiological understanding. In particular, a remodeling of the gut mucosal cellular microenvironment, such as increased mast cells and T cell activation³ along with histamine, protease, and cytokine release in the colonic mucosa,^{3,4} has been reported in IBS. In addition, some IBS subsets of patients are characterized by increased paracellular permeability,⁵ altered enteroendocrine cell density,⁶ and enteric nervous system (ENS) neuroplasticity. Recent studies have described increased neuronal fiber outgrowth,⁷ density of substance P,⁸ or vanilloid receptor 1 (TRPV1)⁹ nerve fibers. The impact of mucosal factors on the ENS is supported by the evidence that nerve exposure to soluble mediators in supernatant obtained from mucosal biopsies of IBS patients increases the excitability of enteric neurons¹⁰ and evokes neuroplastic changes in the ENS through the contribution of mucosal histamine, serotonin, protease, or nerve growth factor.¹¹

Besides enteric neurons, the ENS is composed of enteric glial cells (EGC) that outnumber them by a factor of 1.3 to 1.9 and 5.9 to 7.0 in the human submucosal plexus and myenteric plexus, respectively.¹² Enteric glial cells are central regulators of neurons, intestinal epithelial barrier, and gut functions, such as motility,^{13,14} which have been described as altered in an experimental model reminiscent of IBS.¹⁵ However, to the best of our knowledge, changes in EGC in patients with IBS have never been thoroughly studied previously.

Enteric glial cells regulate neuronal processes such as neuronal survival¹⁶ and neuro-mediator expression.^{12,17-20} Conversely, enteric neurons can also communicate to EGC, in particular, via adenosine triphosphate (ATP)-dependent P2Y₄/P2Y₁ pathways.^{21,22} Activation of EGC by such pathways leads to glio-glio communication via connexin-43-dependent signaling.²³ Interestingly, glial-specific ablation of connexin-43 leads to a reduced ATP-induced glio-glio Ca²⁺-dependent communication and ultimately to a reduced intestinal motility.²⁴ Consistently, loss of EGC has also been reported to be associated with intestinal dysmotility in both human and animal models of glia ablation.²⁵⁻²⁷ In addition to neuronal/motor functions, EGC also control intestinal barrier functions, such as paracellular permeability,^{17,28,29} which can be altered in IBS.⁵

This study was designed to characterize putative EGC glioplasticity in the colonic mucosa of IBS patients and identify the underlying mediators, focusing on those produced by the mucosal microenvironment. Specifically, we aimed to (i) characterize EGC phenotype in a bio-collection of colonic biopsies from IBS patients and healthy controls (HC); (ii) determine whether IBS supernatants could induce EGC phenotypic and functional alterations; and (iii) identify soluble factor(s) and cellular targets responsible for these changes.

2 | MATERIALS AND METHODS

2.1 | Patients and biopsies

Patients referred for colonoscopy for digestive symptoms suggestive of IBS were enrolled in the study. After giving their informed consent according to the guidelines of the French Ethics Committee for Research on Humans (DC-2008-402), they completed a Rome III questionnaire³⁰ and a bowel habit assessment in order to diagnose IBS according to Rome criteria, and to determine the IBS subtype. The inclusion criteria included discomfort or abdominal pain at least 3 days per month during the last 3 months, discomfort or pain for at least 6 months, associated with 2 or more of the following: improvement of symptoms with defecation, onset associated with a change in frequency of stool and onset associated with a change in consistency of stool. If the patient had hard stools or separate lumpy stools for over 25% of the time, he/she was labeled as IBS-C; if the stool was loose or watery over 25% of the time, he/she was labeled as IBS-D; and if these 2 types of stools were present over 25% of the time, he/she was included in the IBS-M subgroup. The severity and frequency of abdominal pain and bloating were assessed on a scale from 0 to 4, adapted from previous studies on IBS.⁵ HC answered the same questionnaire and had no digestive complaints. Clinical data were stored in an electronic database (*Integralis*). Biopsies (n = 9/ patient) were obtained for this study using standard biopsy forceps without needle (FB230U; Olympus co., Rungis, France) in the left colon, between 30 and 40 cm from anal verge during the colonoscopy. The biopsies were then placed into physiological serum on ice and immediately transferred to the laboratory.

2.2 | Microdissection and immunohistochemistry

Microdissection was performed as previously described³¹ in 3 biopsies. Each whole-mount preparation was fixed in paraformaldehyde 4% for 3 hours, washed 3 times with PBS (phosphate-buffered saline) 1× and then stored at 4°C in PBS/NaN₃ for later immunohistochemistry. Specimens of mucosa and submucosa were permeabilized for 3 hours in PBS/NaN₃ containing 1% (v/v) Triton X-100 and 10% (v/v) horse serum and then incubated overnight with primary antibodies diluted in permeabilization solution. Whole-mount preparations were then rinsed 3 times with PBS for 30 minutes and secondary antibodies diluted in PBS/NaN₃ containing 10% (v/v) horse serum were added for 3 hours. Primary and secondary antibodies used in all experiments are listed in supporting information (Table S1). Whole specimens of mucosa and submucosa were viewed under an Axio Zoom.V16 stereomicroscope (Zeiss, Marly Le Roi, France). The area occupied by EGC in colonic mucosa from IBS patients and HC was quantified as the S100β immunoreactive area in one field of observation (0, 33 cm²) using ImageJ software. The results are expressed as the mean of 3 fields observed for biopsy.

2.3 | Western blot analysis

Two biopsies per patient were recovered in RA1 lysis buffer to separate RNA and proteins. The same process was used for cultures of EGC treated either with supernatants from biopsies or with drugs.

Samples were processed for electrophoresis using the SDS-PAGE buffer kit (Invitrogen, Saint-Aubin, France) and separated on 4%-12% BisTris gel (Invitrogen). Proteins were transferred to nitrocellulose membranes with the iBlot system (Life Technologies, Carlsbad, CA, USA). After being blocked with Tris-buffered saline, 0.1% Tween 20 and 5% non-fat dry milk for 1 hour, blots were incubated overnight at 4°C with primary antibodies diluted in Tris-buffered saline and 5% non-fat dry milk for rabbit anti-GFAP (glial fibrillary acidic protein) (Dako, Les

Ulis, France, 1/2000) and rabbit anti-S100 β (Dako, 1/500). Immunoblots were probed with the appropriate horseradish peroxidase conjugated secondary antibodies (Life Technologies) and visualized by chemiluminescence (Clarity Western ECL Substrate; Bio-Rad, Hercules, CA, USA) using a Gel-Doc imager and the Image Lab Software (Bio-Rad, Hercules, CA, USA). The value of total protein immunoreactivity was normalized to the glyceraldehyde-3-phosphate dehydrogenase (GAPDH) immunoreactivity and expressed as a percentage of the average of controls.

2.4 | Quantitative polymerase chain reaction (PCR)

RNA from biopsies or cultures of EGC treated with supernatants from biopsies or with drugs was isolated using the Nucleo Spin RNA Triprep Kit or Clean up (Macherey-Nagel, Düren, Germany), respectively, according to the manufacturer's instructions. Potential genomic DNA contamination was removed by treatment with TurboTM DNase (Ambion Inc., Austin, TX, USA) and RNA was quantified using an ND-1000 UV-Vis spectrophotometer (Nanodrop Technologies, Wilmington, DE, USA). cDNA was synthesized from 1 μ g total RNA using the Super Script III Reverse Transcriptase System kit (Invitrogen) and diluted to a final concentration of 8 ng eq RNA/ μ L. qPCR was performed using StepOne Plus (Life Technologies) detection system with Fast SYBR Green (Life Technologies) master mix. The PCR signal was normalized against S6 as reference gene to control for variability in the amount and quality of the RNA. The sense and antisense oligonucleotide primers used in this study are shown in supporting information Table S1.

2.5 | Biopsies supernatant production

Four biopsies were rapidly weighted, and transferred in plastic tubes that were completed with Krebs Hepes solution (1 mL of Krebs Hepes for 30 mg of biopsy). After 20-minute incubation at 37°C and being continuously oxygenated (95% O₂/5% CO₂), the solution was removed and centrifuged at 11 000 RCF (relative centrifugal force) for 1 minute before being filtered with centrifuge tube filters (0.22 μ m, SPIN-X; Corning, New York, USA). Aliquots of 300 μ L of supernatant were stored at 80°C until assays.

2.6 | Cell cultures

Embryonic EGC of rat (cell-lineage *JUG2 Inserm U1235*) were isolated from ENS primary culture derived from rat embryonic intestine (E15)³² according to a procedure previously described.³³ Briefly, after 13 days of culture, primary cultures were trypsinized and seeded in serum-containing media after differential centrifugation. Following 7 days of culture, isolated areas of morphological glial cells-like were trypsinized using cloning cylinder and seeded in culture flask in serum-containing media. They were immunoreactive for GFAP, Sox10, and S-100 β , all glial markers, but not for Tuj-III, PGP9.5, neuronal markers, and smooth muscle actin, a myofibroblast marker.

Enteric glial cells were cultured in 25 cm² flask in Dulbecco's modified Eagle medium (DMEM) Glutamax medium (4.5 g/L glucose; Invitrogen) or DMEM medium (4.5 g/L glucose; Invitrogen) supplemented with 10% heat-inactivated fetal calf serum (FCS) (Abcys, Paris, France), 2 mmol L⁻¹ glutamine (Invitrogen) and 50 IU/mL penicillin, and 50 mg/mL streptomycin (Invitrogen). For Western blot analysis, EGC were seeded at a density of 30 000 cells/well in 100 μ L of medium on a 96-well plate, and cultured for 1 day prior incubation with supernatants, drugs, or control medium (added daily) for 2 days.

2.7 | Flow cytometry analysis

Enteric glial cells were seeded at a density of 10 000 cells/well in 200 μ L of medium on a 96-well plate. Addition of 20 μ L of IBS or HC supernatant was performed at day 1, 3, and 5. At day 7, cell culture supernatants were recovered and transferred in a 96-well conical bottom

plate and then centrifuged for 2 minutes at 2000g. Enteric glial cells were washed with PBS 1X and trypsinized with 0.25% of trypsin EDTA (GIBCO ThermoFisher Scientific, Cillebon sur Yvette, France) for 5 minutes at 37°C. The trypsin reaction was stopped by adding medium containing 10% FCS and then EGC were recovered and placed in the 96-well conical bottom plate. The 96-well conical bottom plate was centrifuged for 2 minutes at 2000g and then PBS/EDTA was added after supernatant removal. Enteric glial cells were re-suspended with 10 µg/mL of 7-aminoactinomycin D (7-AAD) (Sigma) and then fluorescent labeling was measured using a FACS LSR II (BD Biosciences, Le Pont de Claix, France) and analyzed with BD FACS Diva software.

2.8 | Calcium flux assays

Enteric glial cells were seeded at a density of 4000 cells/well in 200 µL of medium on a 96-well plate. The incubation of EGC culture with 20 µL of supernatants or drug/antagonists was performed at day 1 and day 2. After 48 hours of incubation, EGC were washed with PBS and incubated at 37°C in fresh warmed Hanks' balanced salt solution (HBSS) containing 0.5 µmol L⁻¹ fluo-4 AM (wavelength of absorption: 494 nm; wavelength of emission: 516 nm) for 60 minutes. After washing with HBSS, the 96-well plate was placed under Olympus IX 50 inverted microscope with a Olympus DP 50 digital imaging system and Ca²⁺ flux analysis was performed one well at the time after addition of ATP (final concentration of 2 mmol L⁻¹). For each well, a sufficiently dense field of cells was selected to analyze Ca²⁺ flux of 30 cells. The acquisition was fixed with an exposure time of 1 second. The experiment was then recorded for 120 seconds (25 images/seconds) using Cell B software.

2.9 | Calcium imaging analysis

Movies were converted in a sequence of images (JPEG format) with VirtualDub software and analyzed using the ImageJ software with which the outline of 30 individualized cells was traced. Change in fluorescence (F) (calculated as $[\Delta F/F = (F_{MAX} - F_{MIN})/F_{MAX}]$) was calculated. All values were expressed as the percentage of the average of control wells for each separate experiment.

2.10 | Immunohistochemical studies

Enteric glial cells were seeded at a density of 4000 cells/well in 200 µL of medium on a 96-well plate and cultured during 48 hours. Enteric glial cells were subsequently fixed in paraformaldehyde 4% for 10 minutes, washed 3 times with PBS, incubated 30 minutes with PBS/NaN₃ containing 10% (v/v) horse serum, and subsequently, 1 hour with primary antibodies. Enteric glial cells were rinsed 3 times with PBS for 5 minutes and then secondary antibodies diluted in PBS/NaN₃ containing 10% (v/v) horse serum were added for 30 minutes. Nuclei were stained with 4'-6-diamidino-2-phenylindole (*Dapi*) (1:5000, Sigma). Primary and secondary antibodies used in all experiments are listed in Table S2. Fluorescently labeled EGC were viewed under an Axio Zoom.V16 stereomicroscope (Zeiss, Marly Le Roi, France).

2.11 | Pharmacological studies

All drugs were diluted and reconstituted in culture medium. PAR-2 agonist (SLIGRL; Biochem) was used at final concentrations of 10⁻¹, 10⁻³, 10⁻⁵, and 10⁻⁷ µmol L⁻¹. Histamine (Sigma) and serotonin (Sigma) were used at final concentrations of 10⁻², 1, and 100 µmol L⁻¹. H₁ receptor antagonist pirlamine (Sigma) was used at final concentration of 1 µmol L⁻¹.

2.12 | Statistical analysis

All graphs and statistical significance evaluations were performed using GraphPad Prism Software (GraphPad Software, Inc., La Jolla, CA, USA). A Fisher's exact test was used to analyze clinical variables expressed in percentage. Differences between groups were calcu-

lated by a 2-tailed Student's *t* test for non-parametric and unpaired data or Mann-Whitney U test and Kruskal-Wallis non-parametric ANOVA test followed by Dunn's posttest. For the H1R antagonist effect experiments, a 2-way ANOVA test followed by a Bonferroni post hoc test was used. The relation between quantitative variables and clinical data was calculated using a Pearson's correlation coefficient test. Values of $P \leq .05$ were considered statistically significant.

3 | RESULTS

3.1 | Study patients

From December 2013 to March 2015, 34 IBS patients and 24 HC were included. In the overall population, mean age was 48.6 ± 14.8 years and male:female distribution was 36:58 (62.1% female). The clinical characteristics of HC and IBS patients are reported in Table 1. There was no difference in demographic factors and in intensity and frequency of abdominal pain and bloating between IBS subtypes.

TABLE 1 Characteristics of the study population

	Healthy controls (n = 24) n (%) or mean (SD)	All IBS (n = 34) n (%) or mean (SD)	IBS-C (n = 13) n (%) or mean (SD)	IBS-D (n = 10) n (%) or mean (SD)	IBS-M (n = 11) n (%) or mean (SD)
Age (y)	45.2 (13.3)	51.0 (15.6)	46.8 (13.6)	55.1 (14.3)	52.2 (18.8)
Sex male	13 (54.0)	9 (26.5)*	3 (23.1)	2 (20.0)	4 (36.4)
Depression	4 (17.4)	12 (40.0)	5 (38.4)	3 (33.3)	5 (55.6)
Pain intensity	0.08 (0.4)	1.81 (0.8)*	1.6 (0.8)	2.1 (0.7)	1.8 (0.9)
Bloating intensity	0.42 (0.6)	1.54 (0.8)*	1.6 (0.9)	1.5 (0.9)	1.5 (0.9)
Pain frequency	0.13 (0.6)	2.3 (1.1)*	2.3 (0.9)	2.5 (1.0)	2.2 (1.3)
Bloating frequency	0.75 (1.3)	2.5 (1.3)*	2.5 (1.2)	2.7 (1.4)	2.3 (1.4)

* $P < .05$ compared to healthy controls.

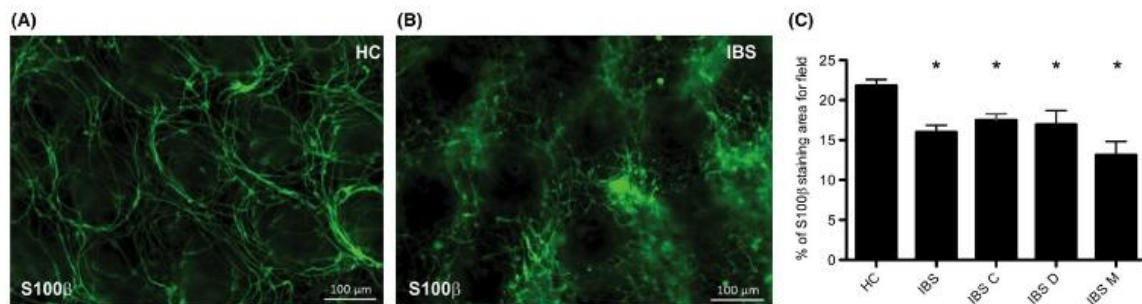


FIGURE 1 Characterization of enteric glial network in colonic biopsies from healthy control and IBS patients. Representative images of glial network in biopsies from a HC (A) and IBS patient (B). (C) The S100β-stained area was significantly reduced in biopsies from IBS patients compared to HC, whatever the IBS subtype (mean of 3 fields for biopsy observed). Data are expressed as mean values \pm SEM of $n = 15$ HC and $n = 26$ IBS patients ($n = 10$ IBS-C; $n = 8$ IBS-D; $n = 8$ IBS-M) * $P < .05$

3.2 | Mucosal enteric glial network

Changes in S100β protein expression were investigated in the mucosa from biopsies of HC and IBS patients using immunohistochemical methods (Figure 1A-B). Quantitative analysis showed that the S100β staining area was significantly reduced by 27% in biopsies from IBS patients as compared to HC ($P < .0001$) (Figure 1C). A similar reduction was shown in all subtypes of IBS. To verify that the difference observed depended on the change of glial intensity and not on the modification of the mucosal architecture, the number of crypts per field of observation was counted and no difference between IBS patients and HC was detected (data not shown). Significant negative correlations were found between the S100β-

stained area and the frequency ($r = -.42$; $P < .05$) and intensity ($r = -.48$; $P < .05$) of pain and bloating ($r = -.37$; $P < .05$) in all IBS subtypes.

There was no difference in S100 β and GFAP expression in all IBS subtypes as assessed by Western blot analysis (data not shown) and PCR. However, S100 β mRNA tended to be linearly correlated with S100 β mucosa density (Figure S1A). Furthermore, S100 β was also moderately correlated with connexin-43 and TNF α expression (Figure S1B and S1C).

3.3 | Effect of mucosal supernatants on EGC proliferation and phenotype

To determine whether soluble factors produced by biopsies were able to induce changes in EGC function and phenotype, we first investigated the effect of IBS supernatants on EGC proliferation.

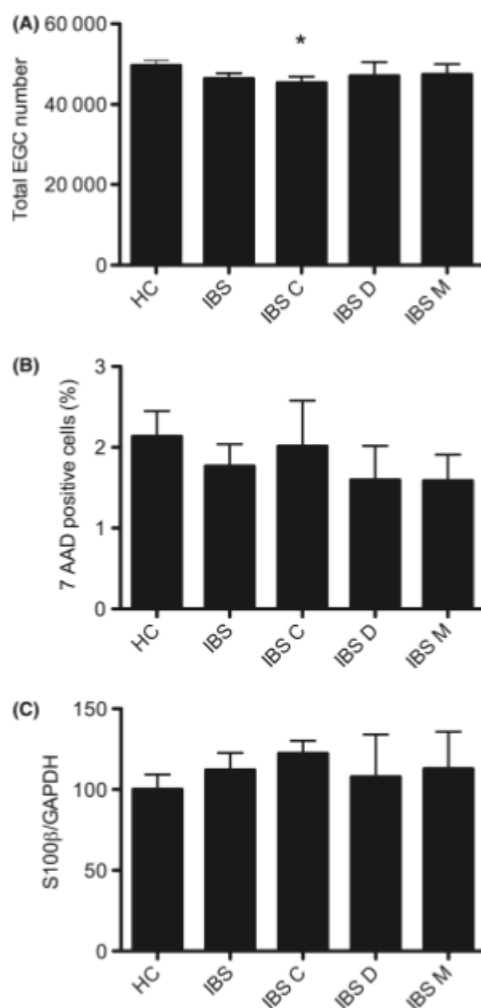


FIGURE 2 Effect of biopsies supernatant on EGC functions and phenotype. (A) There was no difference between the number of EGC treated for 6 days with IBS supernatants and EGC treated with HC supernatants. EGC number was significantly reduced in case of treatment with IBS-C supernatants as compared with EGC treated with HC supernatants. Data are expressed as mean values \pm SEM of $n = 23$ HC and $n = 29$ IBS patients ($n = 12$ IBS-C; $n = 8$ IBS-D; $n = 9$ IBS-M) * $P < .05$. (B) There was no difference in the proportion of 7-AAD-positive cells to total cells after treatment with IBS and HC supernatants. (C) There was no difference in S100 β expression as measured by Western blot in EGC cultured with IBS and HC supernatants. Data are expressed as mean values \pm SEM, normalized to HC, of $n = 9$ HC and $n = 19$ IBS patients ($n = 5$ IBS-C; $n = 7$ IBS-D; $n = 7$ IBS-M)

Following treatment of EGC cultures with IBS and HC supernatants, EGC cell number was evaluated (Figure 2A). The number of EGC was significantly reduced by 9% in cultures treated with IBS-C supernatants, but not IBS-M or IBS-D supernatants, as compared to HC. In addition, the reduction of EGC number induced by IBS-C supernatants was not associated with an increase in cell death (Figure 2B) as assessed by measuring the proportion of 7-AAD-positive EGC. There was a modest negative correlation between the number of EGC cultured with IBS and HC supernatants and the frequency of pain ($r = -.27$; $P < .05$). Treatment of EGC with IBS supernatants did not change the expression of S100 β (Figure 2C) or GFAP (data not shown) proteins as measured by Western blot.

3.4 | Effects of mucosal supernatants on ATP-induced Ca $^{2+}$ response of EGC

We next aimed to determine whether incubation of EGC (48 hours) with IBS supernatants could modify their Ca $^{2+}$ response to ATP. The amplitude of Ca $^{2+}$ response to ATP in EGC cultured with IBS supernatants was significantly decreased as compared to the response in EGC cultured with HC supernatants (Figure 3A-B). These changes in Ca $^{2+}$ response to ATP were dependent on IBS subtype. Indeed, the mean amplitude of Ca $^{2+}$ flux was significantly reduced in EGC cultured with IBS-D and IBS-M supernatants, but not IBS-C, as compared

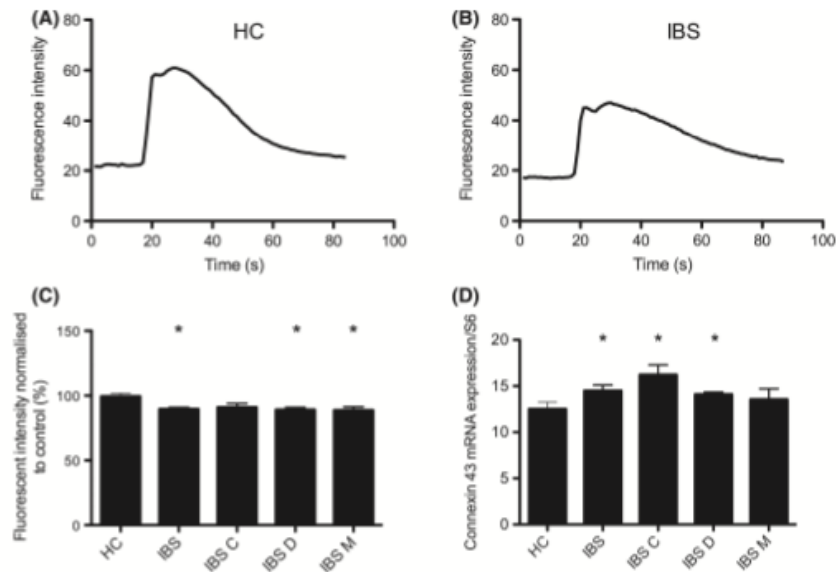


FIGURE 3 Intracellular Ca^{2+} response to ATP in EGC cultured with IBS and HC supernatants. (A, B) Graphics representatives of Ca^{2+} response to ATP in one enteric glial cell after treatment (48 hours) with HC and IBS supernatants. (C) The amplitude of fluo-4 fluorescence intensity in EGC cultured with IBS supernatants, particularly with IBS-D and IBS-M supernatants, was significantly decreased compared to EGC cultured with HC supernatants. Data are expressed as mean values \pm SEM normalized to HC, of $n = 11$ HC and $n = 20$ IBS ($n = 6$ IBS-C; $n = 7$ IBS-D; $n = 7$ IBS-M). * $P \leq .05$ (D) mRNA expression of connexin-43 was significantly increased in EGC cultured with IBS supernatants (48 hours) compared to EGC cultured with HC supernatants, especially in EGC cultured with IBS-C and IBS-D supernatants. Data are expressed as mean values \pm SEM of $n = 7$ HC and $n = 17$ IBS ($n = 5$ IBS-C; $n = 5$ IBS-D; $n = 7$ IBS-M). * $P \leq .05$

to HC (Figure 3C). In addition, the resting Ca^{2+} level was not different in EGC treated with IBS or HC supernatants (data not shown). Furthermore, acute exposure of EGC to IBS ($n = 15$) or HC ($n = 11$) supernatants did not induce changes in Ca^{2+} level (data not shown). Interestingly, the amplitude of Ca^{2+} response to ATP was negatively correlated with pain intensity and frequency (respectively $r = -.53$; $P < .05$ and $r = -.40$; $P < .05$). As connexin-43 plays a role in Ca^{2+} re- sponse to ATP in EGC, we aimed at determining whether incubation of EGC with IBS and HC supernatants could modulate its expression. Connexin-43 mRNA expression was significantly increased by 16% in EGC cultured with IBS supernatants compared to HC. IBS subgroup analysis demonstrated that connexin-43 expression was significantly increased in EGC incubated with IBS-C and IBS-D supernatants as compared to HC (Figure 3D).

3.5 | Mediators involved in supernatant effect upon Ca^{2+} response to ATP in EGC

We next aimed to identify a candidate involved in supernatant effects upon Ca^{2+} response to ATP in EGC. Previous studies have identified mediators such as histamine, serotonin, and proteases as superna- tants mediators that could modulate ENS functions, and in particular neuronal excitability.¹⁰ Based on these findings, we tested the impact of EGC incubation with these mediators on Ca^{2+} response to ATP in EGC. Among the mediators tested, SLIGRL, serotonin, and histamine, only the latter was able to change Ca^{2+} response to ATP as compared to control. Indeed, 48-hour incubation of EGC with histamine ($1 \mu\text{mol L}^{-1}$) reduced Ca^{2+} flux amplitude by 21% (Figure 4).

The expression of histamine receptor on EGC was established by immunohistochemical methods. We first assessed expression of H1R in submucosal plexus of HC and IBS biopsies. Using confocal micros- copy, H1R co-localized with S100 β immunoreactivity at the surface membrane of EGC (Figure 5). Using quantitative immunohistochemis- try, levels of H1R- immunoreactivity were also identical in IBS and HC EGC (data not shown).

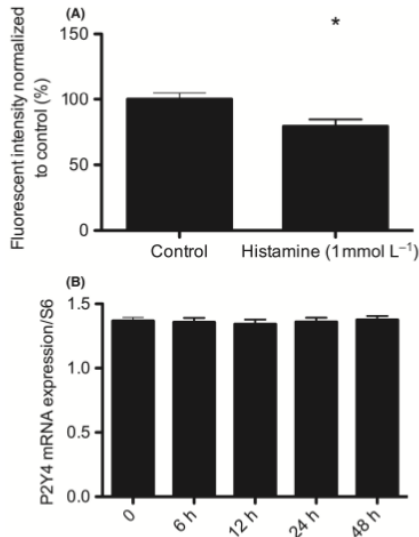


FIGURE 4 Identification of histamine as mediator involved in modification of Ca²⁺ response to ATP in EGC. (A) The amplitude of fluo-4 fluorescence intensity in EGC cultured (48 hours) with histamine (1 $\mu\text{mol L}^{-1}$) was decreased compared to control. Data are expressed as mean values \pm SEM normalized to control, of $n = 11$ independent experiments. * $P < .05$. (B) Time-course analysis of P2Y4 mRNA expression in EGC treated (48 hours, 24 hours, 12 hours, and 6 hours) with histamine (1 $\mu\text{mol L}^{-1}$). No difference was observed at any time compared to control. Data are expressed as mean values \pm SEM of $n = 3$ independent experiments

Pharmacological approaches were applied to establish whether the effects of histamine and IBS supernatants upon Ca²⁺ response to ATP were mediated via H1R activation. Pretreatment of EGC with pyrilamine (1 $\mu\text{mol L}^{-1}$) significantly reversed the changes in Ca²⁺ response to ATP caused by histamine. Moreover, pyrilamine did not modify Ca²⁺ response to ATP in EGC not treated with histamine (Figure 6A). Finally, the effects of IBS supernatants upon Ca²⁺ responses to ATP in EGC were prevented by pyrilamine (Figure 6B). To verify that the decrease in Ca²⁺ response to ATP in EGC cultured with histamine (1 $\mu\text{mol L}^{-1}$) was not due to a modification in the expression of ATP receptors, we performed a time-course experiment to study the expression of mRNA of P2Y4 in EGC treated with histamine (1 $\mu\text{mol L}^{-1}$) during 48 hours, 24 hours, 12 hours, and 6 hours. No difference was observed in the expression of mRNA of P2Y4 in EGC treated with histamine at any time compared to control (Figure 4B). Finally, histamine also did not modify connexin-43

expression and EGC proliferation (data not shown).

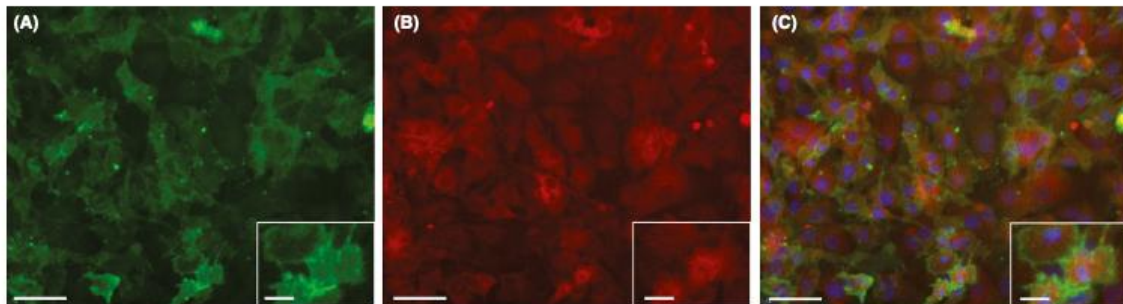


FIGURE 5 Characterization of H1R expression in enteric glial cells cultures. (A-C) Representative images of EGC expression of S100 β (A; green) and H1R (B; red) proteins. (C) Overlay of A-B images and 4-6-diamidino-2-phenylindole-labeled stained nuclei (blue). Scale bar = 50 μm . Enlarged view of boxed areas. Scale bar = 25 μm

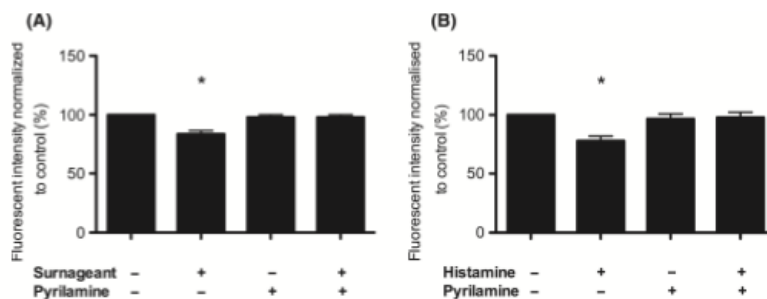


FIGURE 6 Effect of histamine or supernatant from IBS patients on Ca²⁺ response to ATP in EGC. (A) The pretreatment with pyrilamine (1 $\mu\text{mol L}^{-1}$) reversed the significant decrease of Ca²⁺ response to ATP in EGC treated (48 hours) with histamine (1 $\mu\text{mol L}^{-1}$) compared to control. Data are expressed as mean values \pm SEM normalized to control, of $n = 6$ independent experiments. * $P < .05$. (B) The pretreatment with pyrilamine (1 $\mu\text{mol L}^{-1}$) reversed the significant decrease of Ca²⁺ response to ATP in EGC cultured (48 hours) with IBS supernatants. Data are expressed as mean values \pm SEM normalized to HC, of $n = 7$ independent experiments. * $P < .05$

4 | DISCUSSION

This study highlights the occurrence of enteric glioplasticity in the colonic mucosa of IBS patients and identifies histamine as a contributing factor underlying these changes. We first showed a reduced mucosal labeling of S100 β in IBS biopsies as compared to HC, independent of IBS subtypes. Importantly, the S100 β -stained area was negatively correlated with the frequency and intensity of pain and bloating. Next, IBS-C supernatants, but not IBS-D and IBS-M, reduced EGC proliferation. Furthermore, IBS-D and IBS-M supernatants, but not IBS-C, reduced Ca²⁺ response to ATP in EGC. We next showed that these latter changes were blocked by H1R antagonist and reproduced by histamine but not serotonin or PAR-2 agonist (SLIGRL). Overall, our study reveals the occurrence of changes in EGC in IBS that are dependent on the clinical phenotype thus suggesting that EGC abnormalities could contribute to IBS pathophysiology and symptoms.

An important finding of our study was the identification of changes in EGC protein expression in the mucosa of IBS patients. In particular, we showed that S100 β staining was significantly reduced in IBS as compared to HC, although protein and mRNA expression of S100 β remained unaltered. This discrepancy could result from the different methods used. Indeed, immunohistochemistry specifically evaluated EGC (identified by their S100 β immunoreactivity), whereas PCR and Western blot techniques take into account other cell types contained in biopsies besides EGC (immune cells, epithelial cells, and endothelial cells) during normalization. In addition, biopsies also differed one from another in terms of cellular distribution according to their size and depth. To the best of our knowledge, only a preliminary study has examined protein expression in EGC in human intestinal biopsy samples from IBS patients, without observing any changes.³⁴ A recent study performed in an animal model of IBS (maternal separation followed by acute stress) reported structural changes in EGC, such as elongation and/or swelling of terminal processes.¹⁵ Alterations of glial markers have been reported in other diseases such as inflammatory bowel diseases, where a dual expression phenotype was identified, namely an increased expression of S100 β and GFAP in inflamed areas of ulcerative colitis tissues compared to controls, whereas a reduced

S100 β and GFAP expression was observed in non-inflamed areas of Crohn's disease tissues. Surprisingly, in this latter setting, there were no changes in S100 β and GFAP expression in inflamed areas vs controls.¹⁶ This finding is in line with our previous data showing no changes in S100 β or GFAP expression in EGC isolated from Crohn's disease tissues, although arachidonic acid metabolites were reduced in vitro.³⁵ Taken together, these results suggest that EGC could display an altered functional response in IBS regardless of an apparently normal expression of S100 β and GFAP.

Using a validated model of adoptive transfer of disease, we showed that 'long-term' (ie, 48 hours) incubation of EGC with IBS supernatants did not alter the expression of S100 β and GFAP in EGC. We studied the impact of 'long-term' exposure of EGC to supernatants as this approach could allow remodeling of EGC phenotype or functions, which cannot be observed during acute exposure of EGC to supernatants. This is further supported by recent findings demonstrating that chronic exposure of enteric neurons to IBS supernatants reduces rather than increases neuronal excitability.³⁶ In this context, our results showed that long-term incubation of EGC with IBS-C supernatants, but not IBS-D or IBS-M, reduced EGC number in vitro. This effect was not associated with an increased cell death suggesting that IBS supernatants can affect the EGC cell cycle. Whether this property is specific to IBS-C

subgroup should be confirmed on a larger population of IBS patients. However, it is intriguing to observe that (i) animal models leading to a reduction in EGC number or inhibition of their functions result in reduced gut motility and (ii) motility disorders, such as severe slow transit constipation, are characterized by a reduced EGC number. Therefore, it is tempting to speculate that approaches aimed to stimulate EGC proliferation may turn to be useful in motility dysfunctions. The mediator(s) involved in these effects remain(s) to be determined, as histamine did not induce any changes in EGC number. Previous studies have shown that cytokines such as IL1 β , IL-4, IFN- γ , or lipopolysaccharide can modulate EGC proliferation in vitro but their involvement in the present context need to be tested in future studies. A limitation of our study is that the effects of exposure to IBS supernatants were only explored in vitro and in rat EGC isolated from the myenteric plexus. Therefore, whether similar changes occur in vivo and can be extended to other EGC types, such as of submucosal origin, remains to be determined in future studies.

Another major finding of our study was that IBS-D and IBS-M supernatants significantly reduced Ca²⁺ response to ATP in EGC as compared to HC. Recent studies have shown the importance of Ca²⁺ response to ATP in enteric neuroglial communication and ultimately in control of gastrointestinal functions controlled by the ENS.³⁷ Indeed, ATP has been shown to activate P2Y₄ receptors leading to an increase of intracellular Ca²⁺ concentration in EGC, which propagates to the functional EGC syncytium via connexin-43, and ultimately impacting on GI motility. *McClain* et al. also reported reduced expression of connexin-43 associated with reduced glial Ca²⁺ response and altered motility in aging mice.²⁴ Interestingly, Ca²⁺ response to ATP in EGC treated with IBS supernatants was negatively correlated with pain further reinforcing the hypothesis of a functional link between EGC and symptoms. In order to determine mechanisms potentially involved in altered Ca²⁺ response to ATP by IBS supernatants, we first aimed at determining whether changes in EGC expression of ATP receptors (P2Y) could be involved. However, incubation of EGC with supernatants did not modify P2Y₄ mRNA expression. Connexin-43 mRNA expression increased in EGC incubated with IBS supernatants, which was specific for IBS-C and IBS-D but not IBS-M. Whether this increased expression of connexin-43 contributes to maintain a normal Ca²⁺ response to ATP in EGC incubated with IBS-C supernatants or is involved in supernatant-induced reduction in EGC number remains to be determined. Alternatively, the reduced Ca²⁺ response to ATP could also be a consequence of a general change in the cellular Ca²⁺ machinery. Altogether these results suggest that altered ATP-induced Ca²⁺ signaling in EGC could contribute to GI dysfunctions observed in IBS.

An important finding of our study was the identification of histamine as a key soluble factor of the mucosal microenvironment involved in EGC dysfunctions induced by IBS supernatants. Previous studies have reported an increased concentration of histamine in IBS supernatants.³⁸ Interestingly, increased mRNA expression of H1R and H2R was also reported in IBS digestive mucosa.³⁹ Histamine is mainly secreted by mast cells⁴⁰ but food and enteric bacteria are also alternative sources of histamine. Interestingly, a recent study has shown that 58% of IBS patients reported GI symptoms from histamine-releasing food components.⁴¹ The involvement of histamine in the pathophysiology of IBS has been identified in earlier studies^{3,42-44} and emerges as a promising therapeutic target for treating IBS-related symptoms.⁴⁵⁻⁴⁸ In the ENS, histamine has been shown to contribute to increase neuronal activity induced by IBS supernatants.^{38,49,50} Histamine affects enteric neurons via H1R, H2R, and H3R, as demonstrated by the use of selective antagonists (respectively pyrilamine, ranitidine, and clobenpropit).³⁸ To date, the functional impact of histamine

upon EGC remained largely unknown. Kimball et al. reported that acute application of histamine to EGC increased intracellular Ca²⁺ concentration but the receptors involved remained unknown.⁵¹ In contrast in preliminary tests, we were unable to detect a Ca²⁺ response induced by acute application of histamine in EGC. This could also explain the absence of Ca²⁺ response to acute exposure of EGC to IBS supernatants. However, our study adds to the role of histamine onto EGC functions by demonstrating that (i) EGC expresses H1R and (ii) EGC long-term exposure to histamine reduces Ca²⁺ response to ATP via H1R. Although the mechanisms responsible for histamine effects remain to be determined, they probably do not result from histamine-induced reduction in the expression of purinergic receptors. Alternatively, histamine could also reduce ATP-induced extracellular Ca²⁺ entry or Ca²⁺ release by intracellular stores such as endoplasmic reticulum. Interestingly, while the H1R antagonist pyrilamine completely abolished histamine effects upon Ca²⁺ response to ATP, it only partially inhibited the effect of IBS supernatants. This latter result suggests that, in addition to histamine, other soluble factors may contribute to the effects of supernatant upon Ca²⁺ responses to ATP.⁵²

Altogether, our study identified EGC as a novel cellular component that can contribute to IBS pathophysiology and symptom development. Finally, distinct EGC-related mechanisms may influence the IBS phenotype and thereby symptom pattern.

ACKNOWLEDGMENTS

The authors thank the Research Nurses at the Centre d'Investigation Clinique (CIC), as well as the endoscopic staff (physicians and nurses) who participated to the study at the University Hospital of Nantes.

CONFLICT OF INTEREST

No competing interests exist.

AUTHOR CONTRIBUTIONS

NLL, LQ, SH, and PA contributed to study concept and design; TD was responsible for acquisition of data; NLL, LQ, SH, PA, TD were responsible for analysis and interpretation of data; NLL, CB, SBV, EC, and MN contributed to drafting of the manuscript; LQ, CB, SBV, EC, MN, RDG, and GB were responsible for critical revision of the manuscript for important intellectual content; CB, MN, and JBH was responsible for statistical analysis; MN obtained funding; MRD and PN provided administrative, technical, or material support; and EC and MN were responsible for study supervision. All authors approved of the final version of the manuscript.

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