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Tympanic membrane pressure buffering function at quasi-static and low-frequency pressure variations

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Abstract

Deformation of the tympanic membrane is known to contribute to the pressure regulation processes in the middle ear cleft. In this paper we investigated pressure variations in the rabbit middle ear in response to sinusoidal varying pressures applied to the ear canal, with frequencies ranging from 0.5 Hz to 50 Hz and pressure amplitudes ranging between 0.25 kPa and 1 kPa. The transtympanic pressure difference was found to be smallest in the quasi-static range, and quickly increased as a function of frequency. The response curves showed asymmetry, with larger transtympanic pressures when positive pressures were applied in the ear canal. Normalized transtympanic pressure amplitudes remained fairly constant as a function of input pressure, with values in the range of 60% to 70% relative to the applied pressure. The total harmonic distortion of the middle ear pressure signal was calculated and was found to be very small (≤2%) for low-pressure amplitudes and low frequencies. For pressure amplitudes in the order of 0.25 kPa to 0.5 kPa, it increased to about 10% at 50 Hz. When a 1 kPa pressure amplitude was applied, variation between animals became large and distortion values up to 30% at 50 Hz were observed. The results showed that pressure buffering due to tympanic membrane displacement was most effective for compensating small transtympanic pressure loads at low frequencies.

Keywords: middle ear pressure, ear canal pressure, pressure regulation, pressure buffering.

Abbreviations: EC, Ear canal; ECP, Ear canal pressure; ET, Eustachian tube; ME, Middle ear; MEP, Middle ear pressure; THD, Total harmonic distortion; TM, Tympanic membrane.

1. Introduction

The ear is subject to pressure variations over a large frequency range. In the auditory range (20 Hz – 20 kHz), the pain threshold of 120 dB SPL corresponds to a pressure amplitude of 20 Pa. In the very low frequency range (<20 Hz), however, pressure variations occur with amplitudes which can be several orders of magnitude larger: during an airplane liftoff or descent, or a dive under water, pressure variations of several kPa are commonly encountered, and even a simple elevator trip of a few floors leads to a pressure variation of several hundreds of Pascals. The gas exchange processes between the blood perfusion in the middle ear (ME) mucosa and the gases in the ME cleft also lead to a slow buildup of pressure differences between the ME and the environment (Loring and Butler, 1987).

Middle ear pressure (MEP) is regulated by a combination of Eustachian tube (ET) action, gas exchange processes, and deformation of the tympanic membrane (TM). As the TM is flexible, it is deformed by pressure gradients between the ME and the environment, thus changing the volume of the gases enclosed in the ME, and buffering part of the pressure change. The TM is therefore an important factor in ME pressure regulation, but at the same time a deficient regulation of pressure loads can lead to TM pathologies. Sustained ME under-pressure is a common clinical condition which can result in remodeling of the TM with atrophy, retraction pockets, atelectasis, and cholesteatoma including ossicular destruction (Tos et al., 1984; Ars et al., 1989; Sadé and Ar, 1997).

Quasi-static pressure changes in the ME can be measured indirectly with tympanometry in clinical circumstances (Thomsen, 1960) or directly using various other methods. Direct measurements can be done through a perforation in the mastoid (Flisberg et al., 1963; Hergils et al., 1990) or the TM

(Buckingham and Ferrer, 1973; Sadé et al., 1976), as well as insertion of a pressure transducer through the ET (Takahashi et al., 1987). Numerous studies have investigated the influence of such pressures on the deformation of the TM (e.g. Dirckx and Decraemer, 1991; von Unge et al., 1993; Vorwerk et al., 1999; Lee and Rosowski, 2001) and the displacement of the ME structures (e.g. Hüttenbrink, 1988; Rosowski et al., 1999; Salih et al., 2016) using various techniques. Recently, the buffering function of the TM in humans was investigated with measurements of MEP change on test persons that were subjected to external pressure variations due to elevator trips (Padurariu et al., 2016). In such experiments it is, however, not possible to systematically investigate the dependence of the pressure buffering as a function of frequency and amplitude.

In the current work we used an animal model to measure pressure variation in the ME caused by pressure variation in the ear canal (EC). Measurements were taken over a wide range of amplitudes and frequencies, so the gap is bridged between the quasi-static pressure regime and the (very) low auditory frequencies. As the study focuses on the purely mechanical effect of the TM, measurements are done ex-vivo, so that the ET action or gas exchange effects are avoided.

2. Materials and methods

2.1. Sample preparation

Rabbits used in this study were sacrificed using intravenous injection of sodium pentobarbital 60 mg/kg (Dolethal, Ethical Agents Ltd, Auckland, New Zealand). The injection was performed in the vein of the pinna after local surface anesthesia with lidocaine spray (Xylocaine, AstraZeneca, Ukkel, Belgium). All preparations were conducted according to the rules set by the Belgian legislation and the local ethical committee of the University of Antwerp, and were in accordance with the Guiding Principles for Research Involving Animals and Human Beings as adopted by the American Physiological Society. The temporal bone was dissected from the skull. The EC was connected with instant glue (Loctite 401, Loctite, Düsseldorf, Germany) to a 2 cm long plastic tube, through which pressure was applied. At the medial side of the bullae, a hole of 2 mm was drilled using a dental bur. Through the hole, a 2 cm long metal tube was glued with dental glue (OptiBond Solo Plus, Kerr, Orange, CA, USA) to measure the MEP as a function of ear canal pressure (ECP). A miniature pressure sensor (Endevco 8507C-1, Meggit Sensing Systems, Basingstoke, UK) for measuring MEP was connected to the metal tube using a 3-way valve so that the ME could be vented before starting measurements. Specimens were kept humid during the preparation and measurement by using an ultrasonic humidifier (BU-1300, Bonaire, Salisbury, Australia).

2.2. Pressure generation

A custom-built pressure generator was used to apply sinusoidal pressure changes to the EC. As shown in Figure 1, the pressure setup consists of an electromagnetic actuator (Vibration Generator (2185.00), Frederiksen, Endeavour Hills, Australia) that is attached to an adaptable volume connected to a tube. When the actuator moves, the volume and hence the pressure of the enclosed gas change, since the amount of gas remains constant. With a pressure sensor (PDCR 10/L, Druck, Inc., New Fairfield, CT, USA) coupled to the tube, the pressure values were measured and used in a custom-built feedback system (Aernouts and Dirckx, 2011). This way the actual pressure follows the desired values with an accuracy of better than 2% over the entire frequency and pressure range. The feedback control unit (FU) was connected to a function generator (TDS 210, Tektronix, Beaverton, OR, USA), and was used to generate sinusoidal pressure changes with frequencies varying from 0.1 to 100 Hz within the range of -2 to +2 kPa. The calibration of the pressure generation system and the MEP pressure sensor were checked extensively, and proved to be perfectly stable within the measuring resolution over long periods of time (months).

2.3. Measurement protocol

With an A/D port (NI DAQPad-6015, National Instruments, Austin, TX, USA) connected to a PC, pressure generation and measurement was controlled from ca ustom written software in Matlab (Mathworks, Natick, MA, USA). The setup allowed to apply pressures with a precision of 10 Pa. Measurements were conducted in fresh specimens, within less than 20 minutes after sacrificing the animal. Four periods were recorded after completing two initial pressure cycles, so that the specimen was preconditioned to reduce viscoelastic effects. Pressures at both the EC and ME were measured simultaneously, so that the time-dependent response of the TM could be obtained. ECPs with amplitudes of 0.25, 0.5 and 1 kPa and frequencies of 0.5, 1, 2, 5, 10, 20, 30, 40 and 50 Hz were applied. The specimens were ventilated before each cycle of pressure measurements. In this way the measurement always started at zero pressure. This measurement protocol allowed us to minimize static pressure gradient build-up, which can occur due to changes in environmental conditions (e.g. changing barometric pressure due to weather conditions, draft due to room ventilation systems etc.). Results using low-pressure amplitudes were recorded first to avoid possible effects of inelastic deformation caused by the higher pressure values. After the measurements, a static under-pressure and over-pressure of 2 kPa was applied to the ear to check for ET opening action, but no leakage was observed.

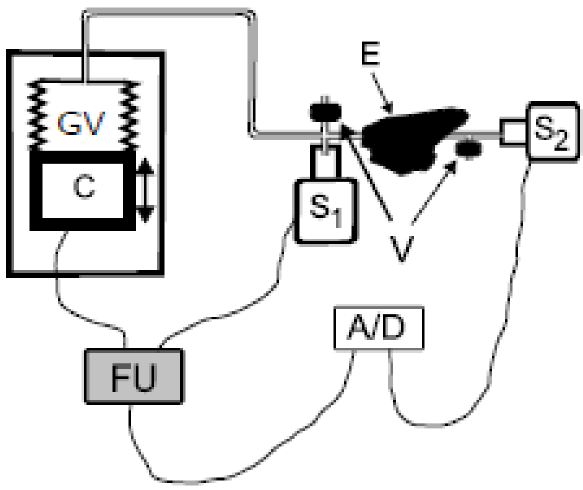

Figure 1: Schematic drawing of the experimental setup; (GV): compressible gas volume, (C): electromagnetic actuator, (S1): pressure sensor to measure the actual pressure generated by the system which is applied to the EC, (FU): feedback control unit, (S2): pressure sensor to measure the MEP, (V): two valves used to ventilate between measurements, (E): specimen, which is glued via two tubes to the pressure sensors and (A/D): A/D port that sends/receives the signals to/from a PC.

When the actuator (C) moves, the pressure in the gas volume (GV) changes as the total gas content remains fixed. With the feedback control unit (FU) a desired pressure value is obtained.

2.4. Total harmonic distortion

It is well known that the TM and ME show nonlinear behavior in the quasi-static regime at large pressure amplitudes (Hüttenbrink, 1988; Dirckx and Decraemer, 1991, 1992; Aerts and Dirckx, 2010). Consequently, a nonlinear pressure response as a function of ECP is to be expected. To quantify the level of such a nonlinearity, the total harmonic distortion (THD) was calculated, which is a popular method to specify nonlinearity in acoustic signals (Aerts and Dirckx, 2007). This is achieved by considering the Fourier transform of the pressure signal at the excitation frequency and the corresponding higher harmonics. To calculate the THD, the amplitudes of the contributions of the higher harmonics are first squared and summed. Then, the square root of this component is divided by the amplitude of the contribution of the excitation frequency.

3. Results

Figure 2 shows an example of the measured MEP and ECP signals obtained at 0.5 and 50 Hz (amplitude of 1 kPa). The figure shows that the MEP follows the waveform of the ECP at lower frequencies, while the deviation between the two waveforms increases at higher frequencies. The figure also shows that both ECP and MEP curves have a small offset of a few Pa. For the higher pressure amplitudes like the one in the figure, this offset and its variation over time negligible, but for the lowest amplitudes (0.1 kPa) it causes a slight drift of the curve over time. Hence, only a single period will be used to do calculations. The results obtained in the several periods are very repetitive indicating that stable preconditioning has been reached.

In the time graphs shown in Figure 2 it is difficult to see the relationship between applied pressure (ECP) and resulting pressure (MEP). Therefore, all results will be shown in a different representation. For each measurement MEP is plotted as a function of ECP for one period of the recorded time signals. For the 6 specimens, MEPs as a function of ECPs for amplitudes of 0.25, 0.5 and 1 kPa are presented in Figures 3, 4 and 5 respectively. All specimens exhibited similar behavior for each amplitude and frequency, apart from specimen #R2, which shows markedly larger hysteresis than the other samples. For 0.25 kPa amplitude, all curves are nearly straight lines with a slope in the order of 0.3. Most curves go through (0, 0), although for some measurements there is a small offset. For one ear the offset is a bit larger (0.05 kPa). At 50 Hz all curves start to show a little hysteresis. The curves recorded for the higher pressure amplitudes (0.5 kPa and 1 kPa) show clearly larger hysteresis, which also increases with frequency. The hysteresis contributes to distortion of the curve which we analyze further below. The overall slope of the curves is larger for the 0.5 kPa measurements, with a value of about 0.4. For the 1 kPa measurements the curves deviate clearly from a straight line and start to show the typical *S*-shape found in other studies using pressure gradients in the range of several kPa.

To analyze the pressure buffering effect as a function of frequency, the maximal transtympanic pressure gradient (ECP - MEP) as a function of frequency is presented in Figure 6. The figure shows that the transtympanic pressure gradient rapidly increases when frequency increases from 0.5 Hz to a few Hz. Beyond a few Hz the gradient increases slowly as a function of frequency. The ratios of transtympanic pressure over ECP are presented as a function of ECP in Figure 7. This normalized value is fairly constant for all frequencies. Also as a function of ECP the value is nearly constant between amplitudes 0.5 kPa and 1 kPa. At the lowest ECP amplitude (0.25 kPa) the value is slightly higher.

As shown in Figure 2, the ECP has an almost perfect sinusoidal shape, and thus it has a very small THD value (less than 2%). In order to take into account the small nonlinearity of the input signal, we subtracted the THD of the ECP from the THD of the MEP. The results are shown in Figure 8 for input pressure amplitudes of 0.25, 0.5 and 1 kPa. For all ears and all pressures one sees that THD increases as a function of frequency. For all pressure amplitudes the THD of the ME response curve increases as a function of frequency, but the slope of the increase diminishes with increasing frequency. For all pressure values the THD drops sharply at the lowest frequency (0.5 Hz). For ECP values 0.25 kPa and 0.5 kPa the variability between the ears is much smaller than for ECP = 1 kPa where two ears show a THD which is three times larger than in the other ears.

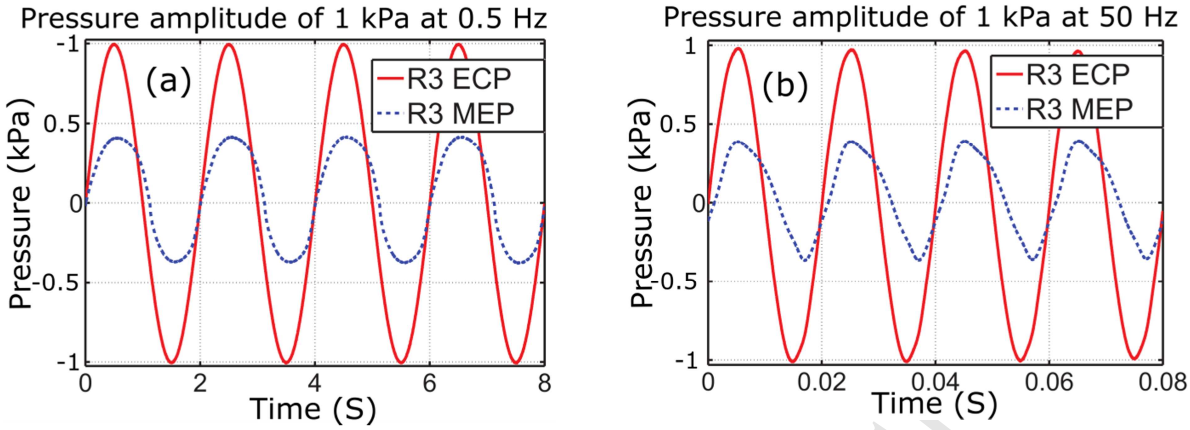

Figure 2: R3 ECP and MEP as a function of time at frequencies of: (a) 0.5 Hz and (b) 50 Hz.

Figure 2 shows that the MEP curve is not sinusoidal, meaning that the TM displacement response as a function of pressure is not linear. In section 4.3 and 4.4 these aspects will be analyzed in more detail.

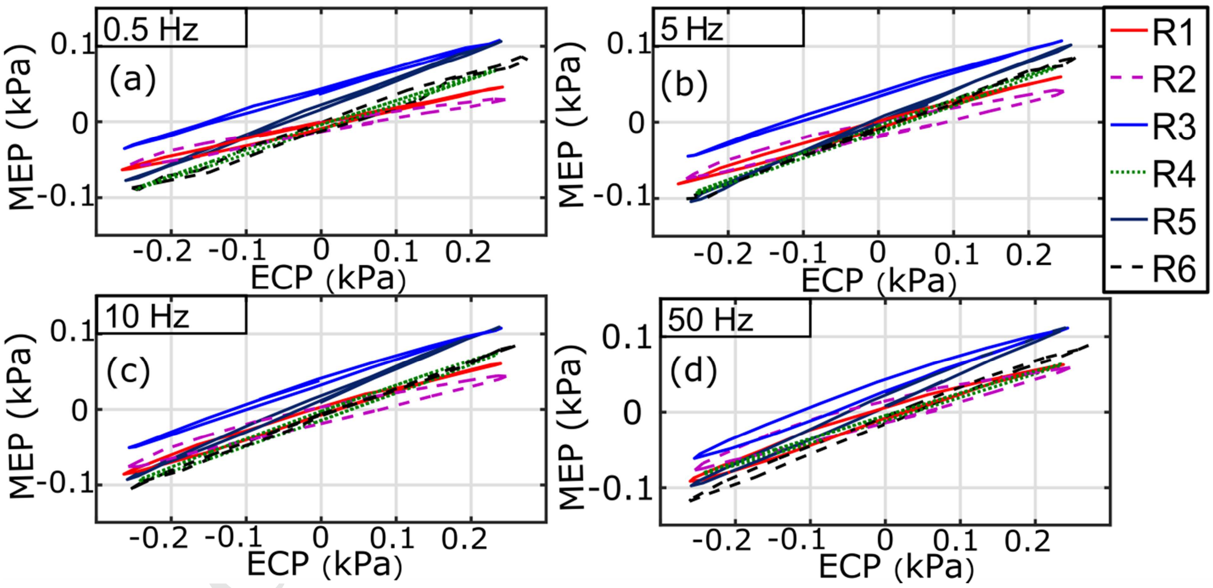

Figure 3: MEP as a function of ECP for an ECP amplitude of 0.25 kPa and frequencies of: (a) 0.5 Hz, (b) 5 Hz, (c) 10 Hz and (d) 50 Hz.

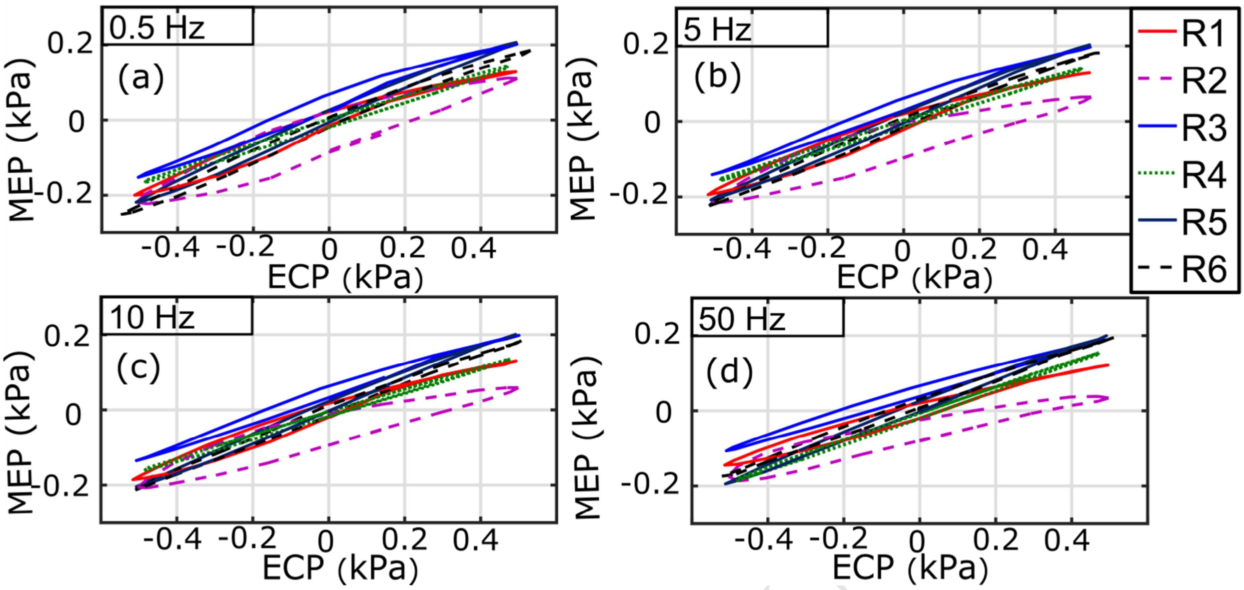

Figure 4: MEP as a function of ECP for an ECP amplitude of 0.5 kPa and frequencies of: (a) 0.5 Hz, (b) 5 Hz, (c) 10 Hz and (d) 50 Hz.

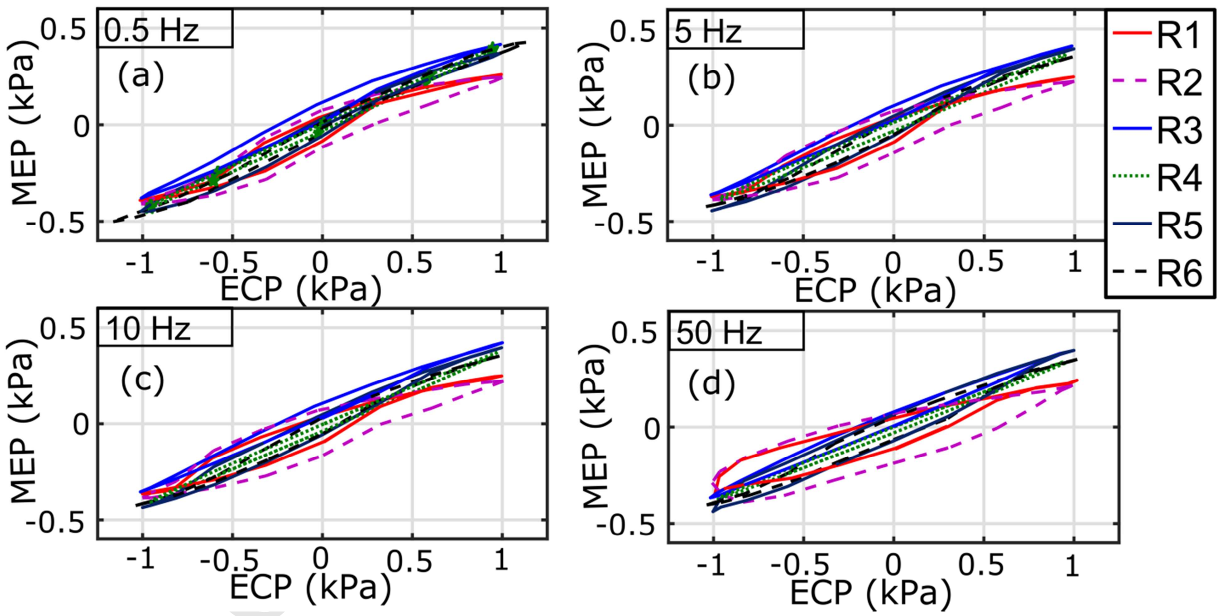

Figure 5: MEP as a function of ECP for an ECP amplitude of 1 kPa and frequencies of: (a) 0.5 Hz, (b) 5 Hz, (c) 10 Hz and (d) 50 Hz.

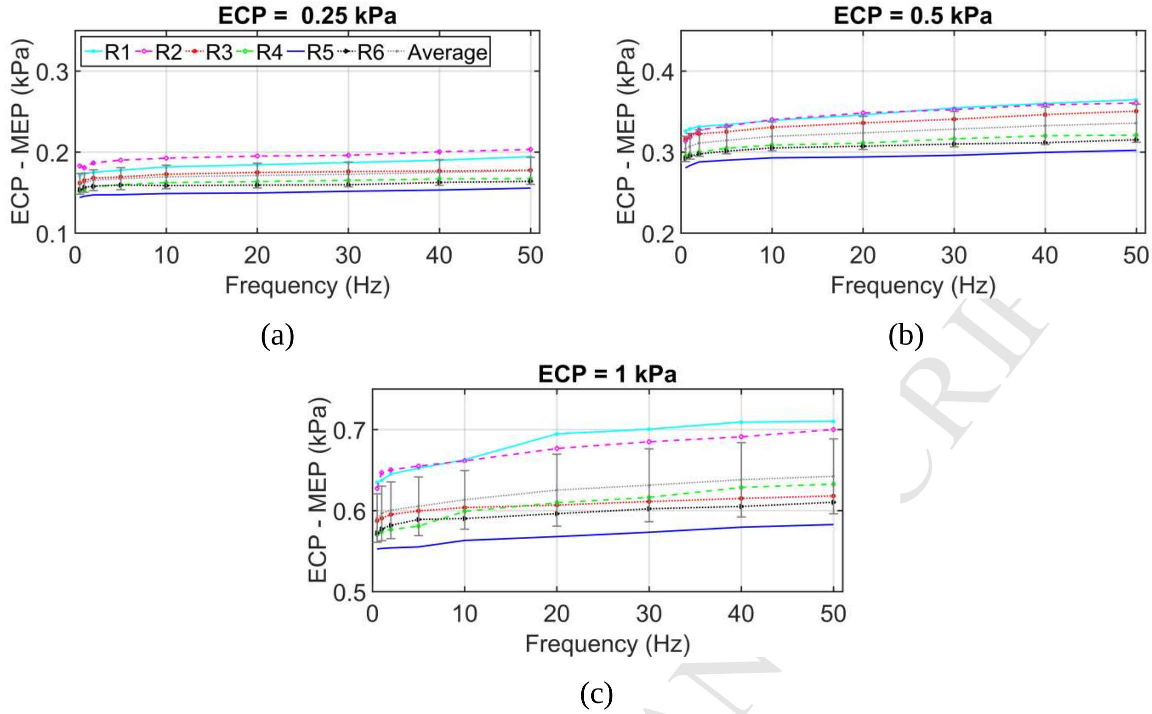

Figure 6: Transtympanic pressure as a function of frequency for ECP amplitudes of: (a) 0.25 kPa, (b) 0.5 kPa and (c) 1 kPa.

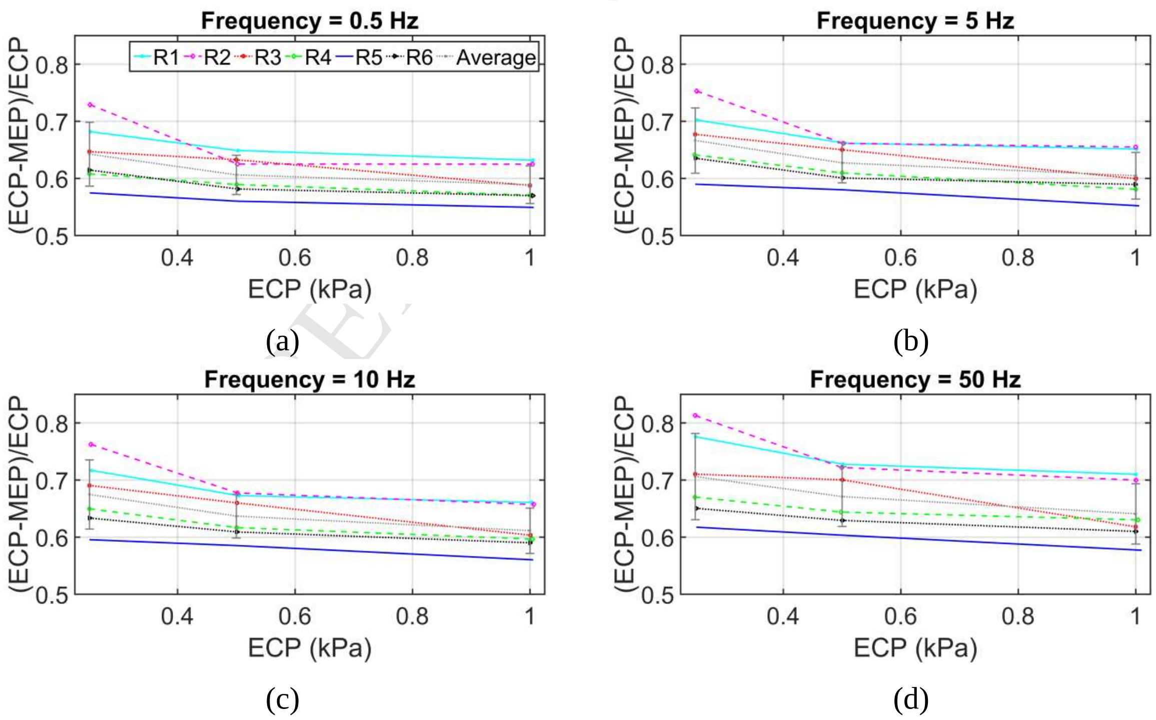

Figure 7: Normalized transtympanic pressure as a function of the input pressure (ECP) at frequencies of: (a) 0.5 Hz, (b) 5 Hz, (c) 10 Hz and (d) 50 Hz.

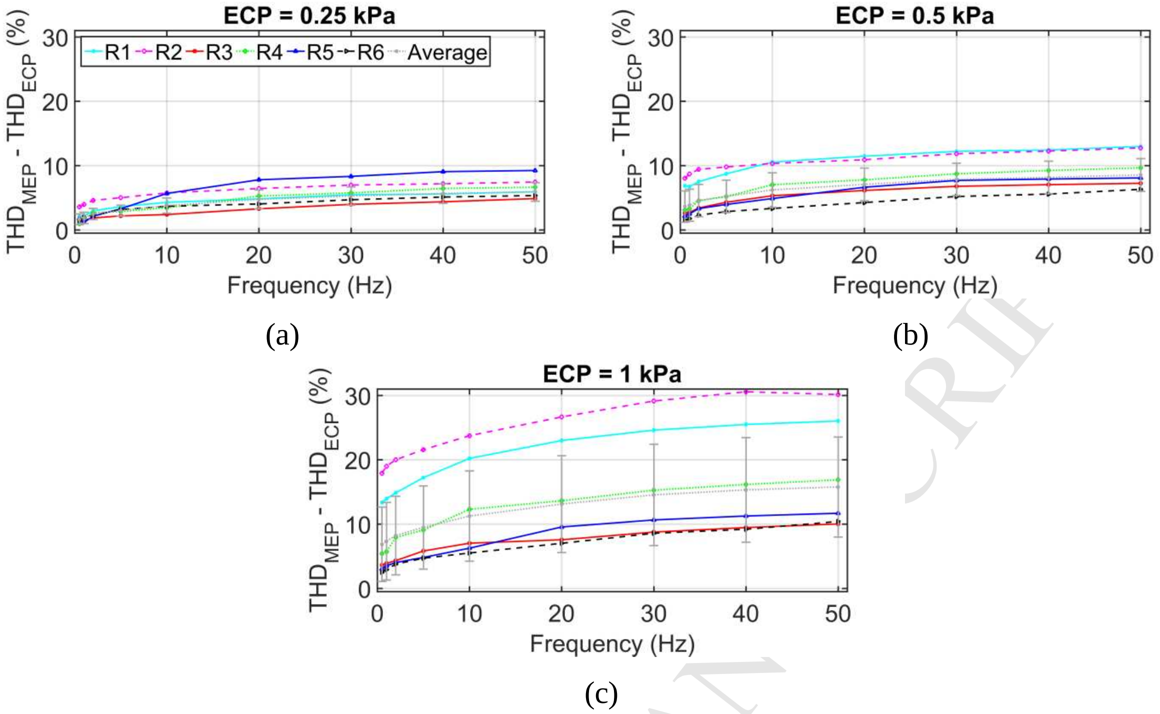

Figure 8: The absolute total harmonic distortion of MEP as a function of frequency for ECP amplitudes of: (a) 0.25 kPa, (b) 0.5 kPa and (c) 1 kPa.

4. Discussion

4.1. Choice of animal model

In hearing research, several animal models have been adopted, each with specific advantages and disadvantages regarding morphology, ME size and animal availability. For the current work we preferred rabbit over the more commonly used gerbil because the gerbil ME volume is even smaller than the rabbit ME volume, and the very thin-walled bulla makes it difficult to connect tubes going to the pressure transducer. Moreover, the dead volume added by the tubes and the transducer become relatively large as compared to the volume of the system under study. Chinchilla has a ME volume comparable to rabbit and has been used in several animal studies (e.g. Ruggero, 1990; Ruggero et al., 1997; Recio-Spinoso et al., 1998), but in Europe the animal is not available for experimental use. A small ME volume makes accurate measurement of pressure changes more challenging due to the inevitable dead volume added by the pressure sensor. In rabbit the total ME gas volume is about 300 µl (Dirckx et al., 2008), while the dead volume of the miniature *Endevco* pressure transducer is equal to 0.8 µl. In earlier work on ossicles movement induced by low-frequency pressure variation, the rabbit was also used as animal model (cf. Salih et al., 2016).

The human ME cavity is coupled to the mastoid, which adds a large volume of gas to the system, while the rabbit ME (just like gerbil and chinchilla) is enclosed in a bulla. The surface area of the rabbit TM is about 34 mm^2 (Salih et al., 2012), and the ME gas volume is of the order of 300 µl (Dirckx et al., 2008), so the ratio is 113 m^{-1}. Recent detailed measurements of human TM surface area reported an average value of 65.6 ± 5.6 mm^2 (De Greef et al., 2015). Other reports gave values of 68.3 mm^2 (Nummela, 1995; Hemilä et al., 1995), 60 mm^2 (Rosowski, 1994) and 57-64 mm^2 (Kirikae, 1960). Recently the average volume of the ME cleft was reported to be 9.7 ml (Padurariu et al., 2016). Other authors report a ME cleft volume of 15 ml (Csakanyi et al., 2011) and mastoid volumes of 10.4 ml (Cros et al., 2016), 9 ml (Park et al., 2000) and 6 ml (Cinamon and Sadé, 2003). Using the most recent data (De Greef et al., 2015; Padurariu et al., 2016), the ratio of TM surface area over ME cleft volume is 6.7 m^{-1}, which is a factor of 17 smaller than the ratio in rabbit. For the gerbil, the TM surface area is 19.9 mm^2 (Buytaert et al., 2011) and the ME volume is 0.233 ml (Buytaert et al., 2011), yielding a surface to volume ratio of 85.4 m^{-1}, which is closer to the value found in rabbit. For the chinchilla, the TM surface area is 60.44 mm^2 (Vrettakos et al., 1988) and the ME volume is 1.52 ml (Vrettakos et al., 1988), giving a surface to volume ratio of 39.8 m^{-1}. These estimations suggest that quantitative values of e.g. buffering capacity may differ strongly between rabbit and human. Despite these differences, the basic elements of the human ME are also found in other terrestrial mammals, such as the rabbit, containing a specialized TM for the reception of sound, an ossicular chain composed of three bony ossicles coupled and supported by several ligaments, an air-filled ME cavity, an ET to maintain aeration of the cavity, and ME muscles that tense the TM and ossicular ligaments causing alterations in sound transmission (Rosowski, 1994). Therefore one could expect that the qualitative results of the current study, namely better buffering at very low frequencies and at low pressure values, and harmonic distortion of TM response at high pressure levels, also hold for human ears.

4.2. Measurement setup

The pressure generator coupled to a feedback system allowed us to apply a desired pressure value to the EC with a resolution of 10 Pa. In this way the measurement accuracy ranged between 2%, for 0.25 kPa, and 0.5% for 1 kPa. Moreover, the two sensitive pressure sensors allowed us to measure the pressure at both the EC and ME simultaneously, which was an important factor to quantify the TM pressure response.

The pressures were measured using calibrated pressure transducers. These transducers have a linearity of better than 1%, and their calibration was checked using a high precision pressure calibrator (Fluke 700PD2, Fluke, Everett, WA, USA). During the experiments no further control measurements were needed as the calibration of the transducers and their amplification electronics remain stable over many months. As we are measuring extremely low pressure values, trivial environmental changes such as opening a door, changing weather conditions, a draft or wind can lead to small offsets in the base pressure value. To exclude this effect, the ears were ventilated between each recording. As shown in Figure 2, the average pressure value then remains stable over the measurement period, and recordings can be made in a stable repeatable way.

Experiments in this study were performed ex-vivo because effect of gas exchange processes and ET opening needed to be avoided. The system under study is governed purely by the passive mechanical behavior of the TM and ossicles. However, in the living animal, one may expect that voluntary or involuntary openings of the ET will occur, partly or completely equilibrating the transtympanic pressure gradient. In the current work, we wanted to focus on the pressure buffering exerted by the TM, thus the ET action needed to be excluded. Nonetheless, no ET leakages were detected when applying static pressures of -2 and +2 kPa to the prepared specimens. From the clinical point of view, the situation with excluded ET action is relevant to pathologies with impaired or blocked ET function. As the pressure buffering by TM deformation is a passive mechanical action, one may expect that it behaves the same for the living and the dead animal.

Specimens were preconditioned before the start of the measurements. Preconditioning is a phenomenon in which tissue behavior changes due to repetitive loading-unloading experiments. In hearing research, several studies have demonstrated this phenomenon (e.g. Gaihede, 1996; Aernouts and Dirckx, 2012). TM preconditioning was reported to be relevant and necessary to reduce artefacts, leading to more stable results of TM deformation in response to pressure loads, and application of 3 preconditioning cycles has been shown to be adequate (Gaihede, 1996). In line with this, Figure 2 shows that stable results are indeed obtained over subsequent pressure periods.

4.3. Transtympanic pressure difference

Figure 2 showed ECP and MEP as a function of time to give an example of the directly recorded signals. To gain understanding of the pressure buffering effect it is more instructive to plot resulting pressure (MEP) as a function of applied pressure (ECP), this representation was chosen in Figures 3-5. In these figures, MEP is plotted as a function of ECP at frequencies ranging from 0.5 Hz to 50 Hz and for pressure amplitudes ranging from 0.25 to 1 kPa. Figure 3 showed a methodological problem associated with the smallest pressure range: even though we ventilated the ear immediately before the measurement, sometimes a small static pressure was present: for most ears the curves were nicely centered around zero, but for a few measurements pressure offsets up to about 0.05 kPa existed. These very small pressure offsets can be caused by changes in environmental pressure or even by bending of a connection tube while closing the ventilation valve. At all frequencies and pressure ranges, the relationship between ECP and MEP showed some hysteresis. Sample #R2 is a bit different from the other ears, with significantly larger hysteresis and smaller MEP values, especially for positive pressures. This behavior might be due to TM pathology such as otitis media with effusion or myringosclerosis, which have been shown to increase ME viscoelasticity (Gaihede et al., 2005) and hysteresis (Gaihede et al., 1997), respectively. However, the MEs were checked to be air-filled, so the sample may simply represent an outlier among healthy rabbits.

In general, one can see that MEP values were about half of the ECP values, demonstrating a clear pressure buffering capacity of the TM. For positive ECPs, smaller absolute values of MEP were observed than for negative ECPs, so transtympanic pressures were the largest for positive ECPs. This effect may be a consequence of the conical shape of the TM and the presence of the ossicles, making movements towards the ME more difficult than inflation movements towards the EC: if the TM moves less, pressure compensation due to volume change is less, resulting in larger transtympanic pressure. This agrees with the asymmetry associated with the "pumping direction" in tympanometry as observed by Therkildsen and Gaihede (2005).

From Figure 6 one sees that the transtympanic pressure difference increases slightly as a function of frequency, but it decreases rather sharply when the frequency decreases below 5 Hz. Under normal physiologic conditions, very large pressure fluctuations mainly occur at these very low frequencies, induced by processes such as gas exchange in the ME, changes in meteorological conditions or altitude changes. At these very low frequencies, transtympanic pressure loads are the smallest so pressure buffering due to TM displacement works at its best.

Figure 7 showed the normalized transtympanic pressure difference as a function of pressure applied to the EC. Transtympanic pressure of course increases with ECP, so we plotted the normalized value to better see the relative regulation effect of the TM. The normalized transtympanic pressure remained fairly constant at values between 60% and 70% as a function of ECP, except for the very small ECP value of 0.25 kPa, where the value increased a bit. This means that at lower pressures less ECP was transferred to the TM and ME than at higher pressures.

4.4. Nonlinearity of tympanic membrane response

In Figure 8 the THD as a function of frequency was presented for the different applied pressure amplitudes. At all pressure values one sees that THD increases as a function of frequency. Especially at frequencies below 5 Hz, THD decreases strongly. The increase of THD with frequency can possibly be attributed to the combined effect of inertia and viscoelasticity of the TM. At 0.25 kPa, THD remains smaller than 10% for all ears, and all ears behave fairly the same. However, at 1 kPa very strong differences exist between ears, with two ears remaining in the 5-10% region over the measured frequency range, while three other ears showed THD values up to 18%, 25% and even 30%.

The asymmetry and nonlinearity in the response of TM displacement as a function of pressure can have several sources. The asymmetrical shape of the TM may play an important role in the asymmetry of the response: at ME positive pressures the TM only needs to bend when it is pushed in the lateral direction, while at ME under-pressures it needs to stretch. One can expect that the presence of the tangentially oriented collagen fibers strongly prevent this stretching, making inward motion more difficult than outward motion. To fully understand this process, detailed modelling of the membrane will be needed. The observed nonlinearity may also be due to the viscoelastic properties of the TM as well as to the viscoelastic properties of the ligaments of the ossicular chain. Again, modelling including soft tissue properties will be needed to fully understand the mechanisms underlying the current measurement results.

4.5. Clinical relevance

As explained above, care needs to be taken when interpreting the current data in clinical context as significant differences exist between the human and rabbit ear. Nevertheless, some of the main mechanical findings can be expected to be general for mammal ears, despite the fact that absolute values such as buffer capacity will be very different between species.

The current results show that pressure buffering strongly increases for the lowest frequencies. As discussed in the introduction, long standing ME under-pressure is associated with remodeling of the TM, retraction pockets and its sequelae. The higher pressure buffering capacity of the TM at (ultra) low frequency pressure variations can be a protective mechanism to prevent development of retraction pockets under normal conditions. In normal conditions the average MEP will be close to ambient pressure but low frequency pressure variations will constantly occur as they are common to daily life. In common meteorological conditions, it has been shown that in the course of a few hours ambient fluctuations occur with amplitudes in the order of tens of Pascals (Didyk et al., 2008). A simple trip in an elevator causes pressure fluctuations of 0.4 kPa over a time span of several seconds (Padurariu et al., 2016). During our experiments we encountered pressure fluctuations of 0.1 kPa when closing a door in a ventilated room. In an ear with pathologic pressure regulation (e.g. blocked ET or dysfunctional gas exchange), the TM is constantly in its deformed state and normal pressure buffering ceases to function.

5. Conclusion

We developed a setup which made it possible to measure MEP as a function of small and slow sinusoidal pressure variations applied to the EC. The MEP was measured as a function of sinusoidal varying ECP with pressure amplitudes ranging between 0.25 kPa and 1 kPa, and for frequencies varying from 0.5 Hz to 50 Hz. It has been found that the transtympanic pressure load is the lowest in the quasi-static range, and quickly increases when reaching the range of audible frequencies. The THD in the resulting MEP was very small for low frequencies and pressure amplitudes, which means that the overall TM motion followed the applied pressure well. The THD increased for both higher pressure values as well as for higher frequencies.

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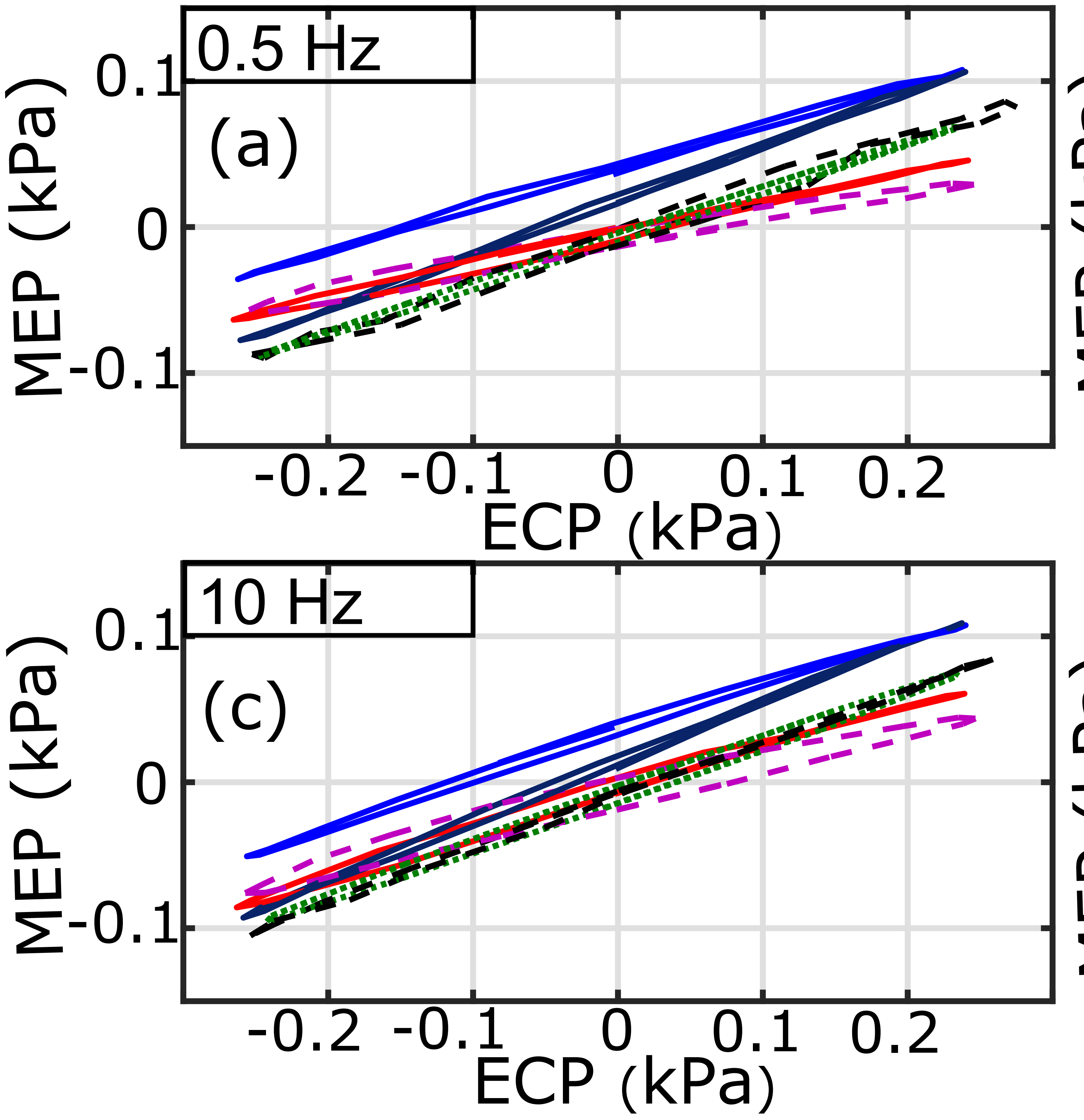
0.5 Hz
(a)
MEP (kPa)
0.1
0
-0.1
-0.2
-0.1
0
0.1
0.2
ECP (kPa)
10 Hz
(c)
MEP (kPa)
0.1
0
-0.1
-0.2
-0.1
0
0.1
0.2
ECP (kPa)

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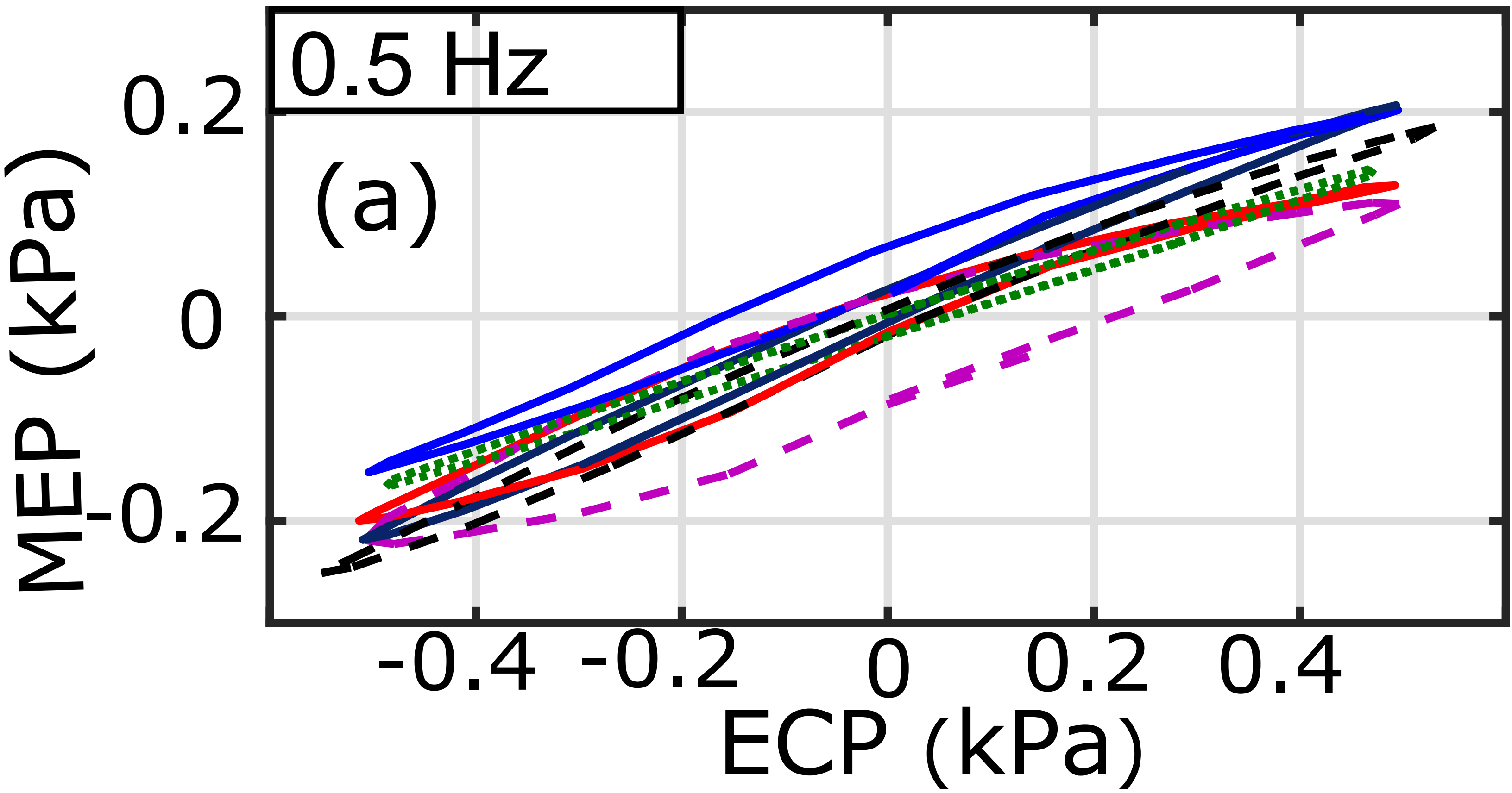
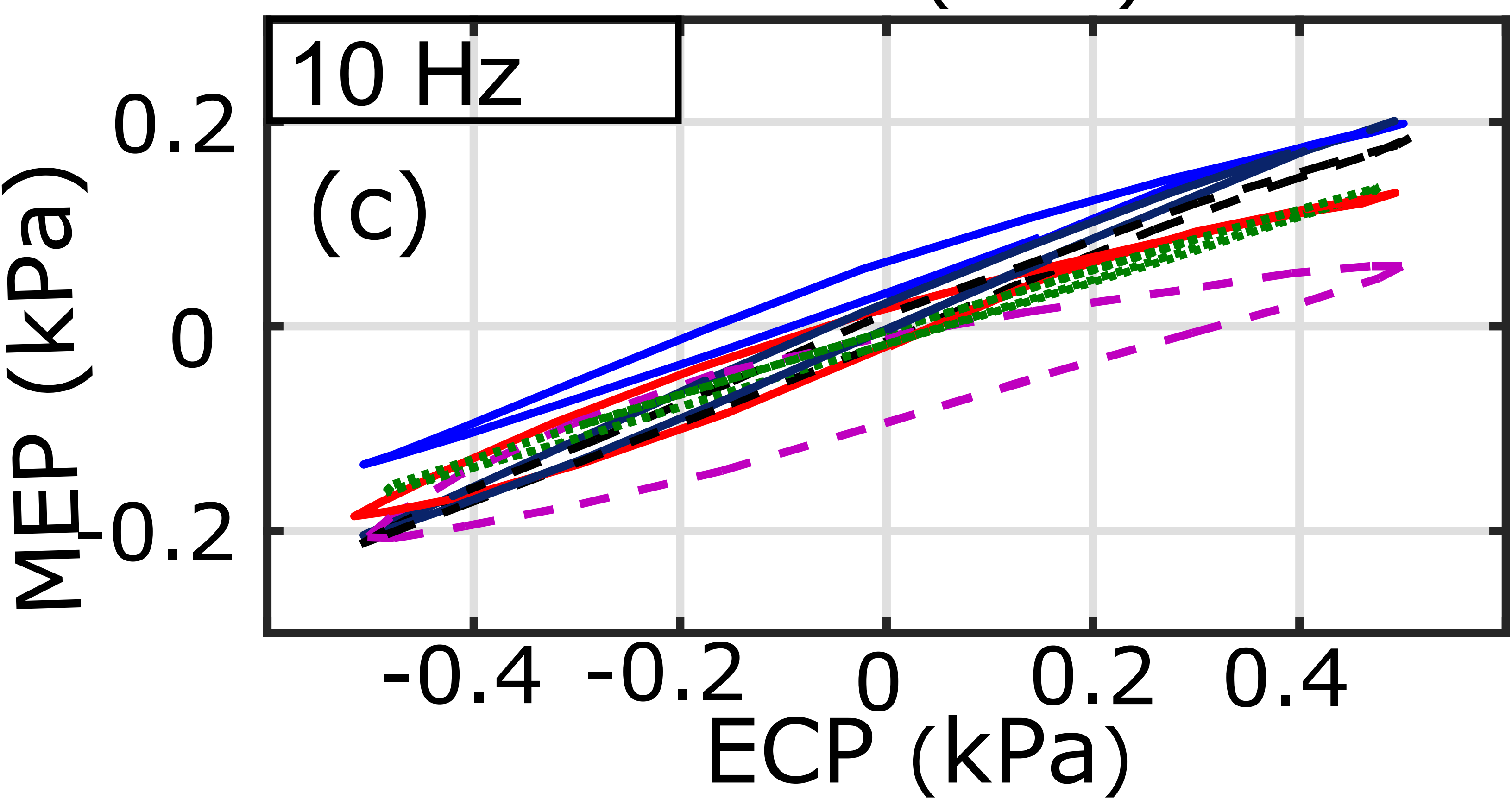
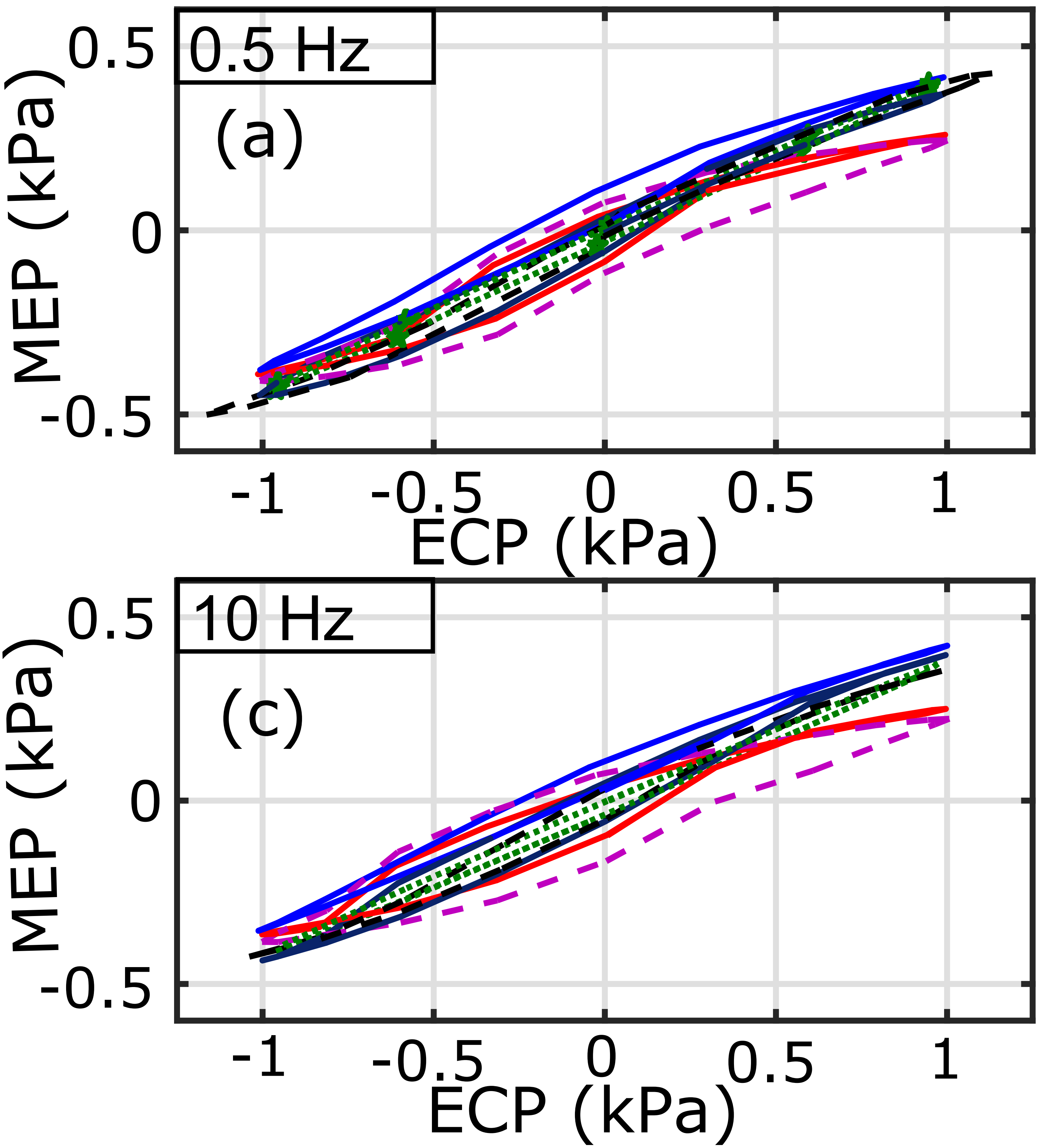
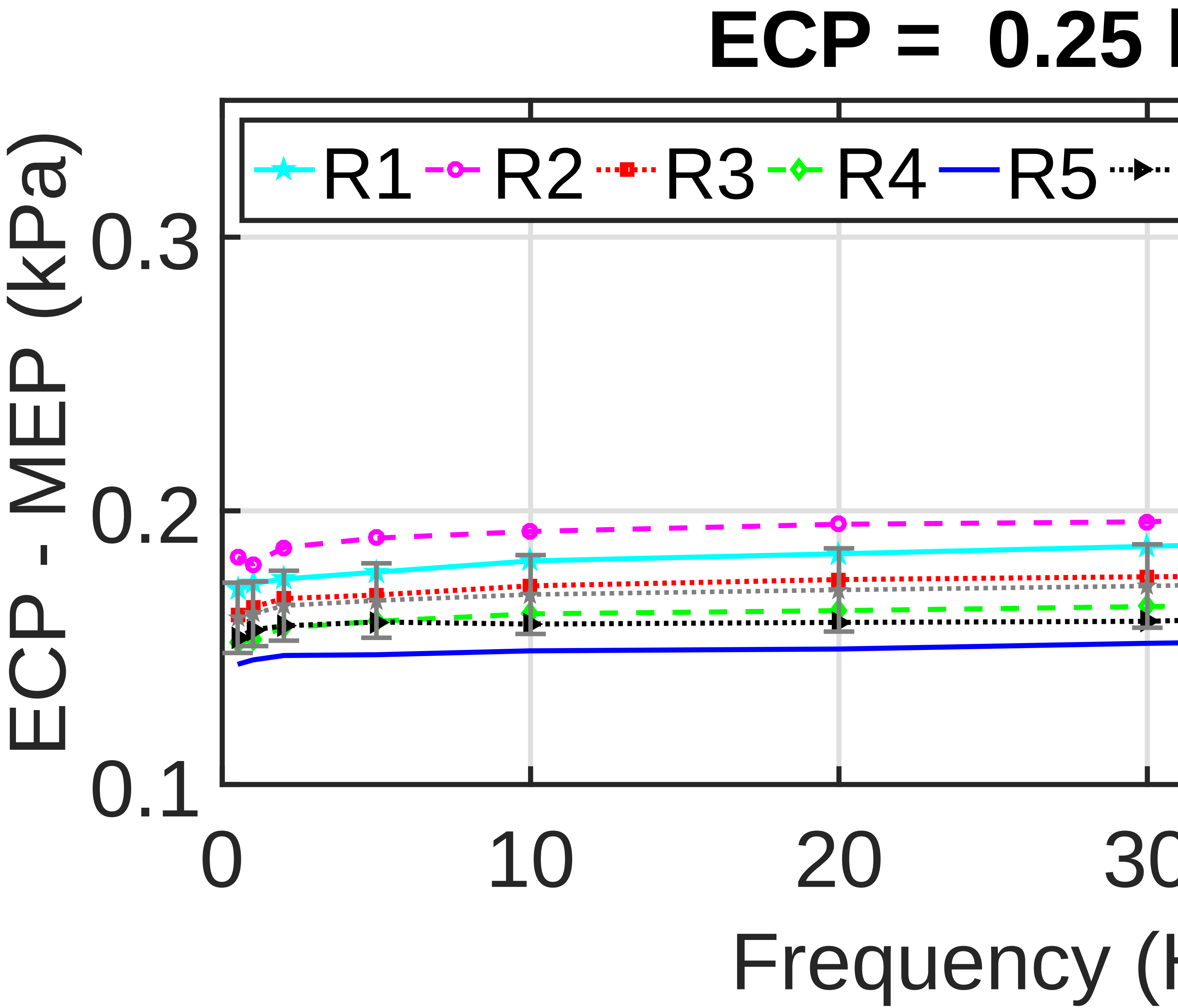
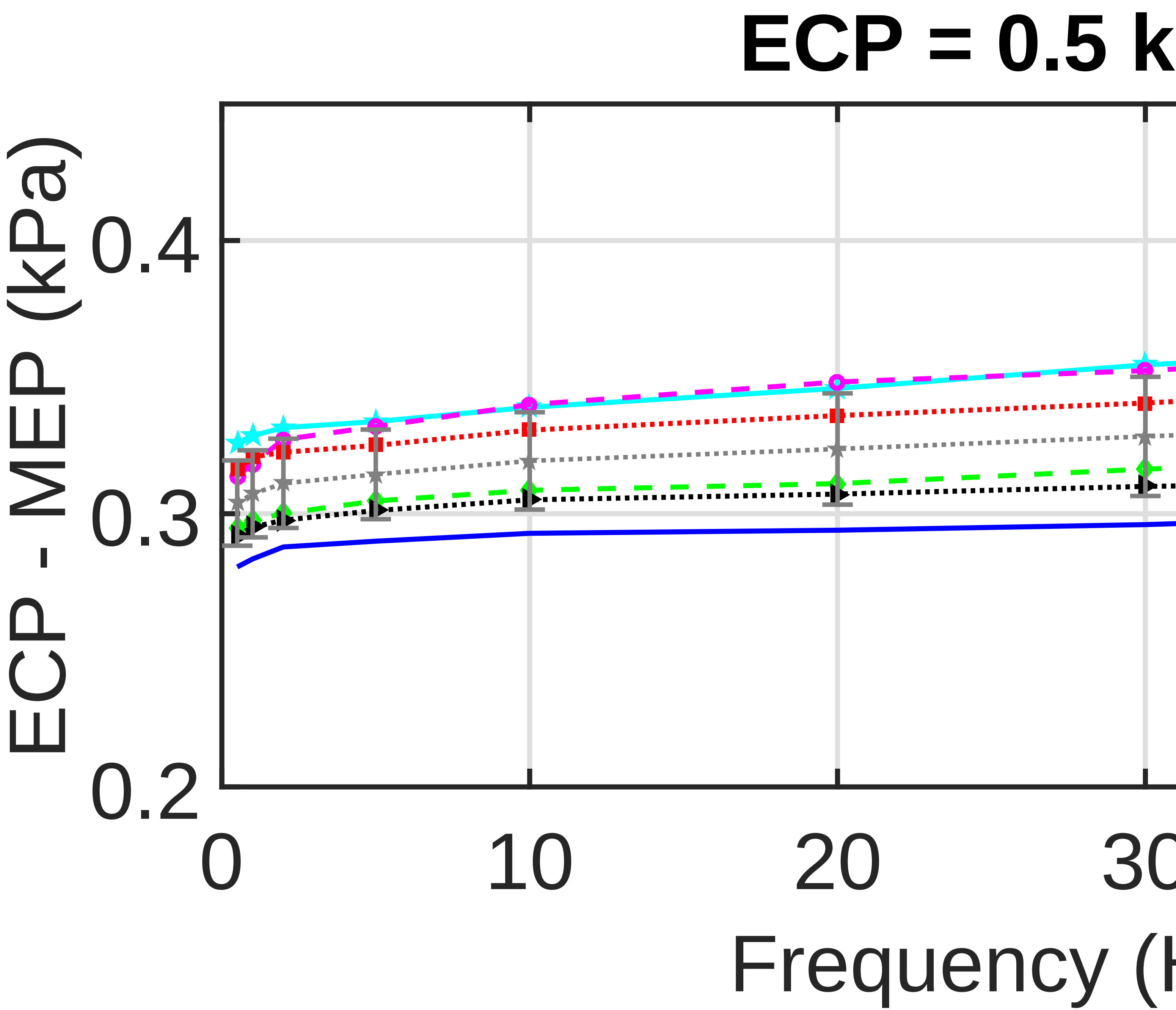


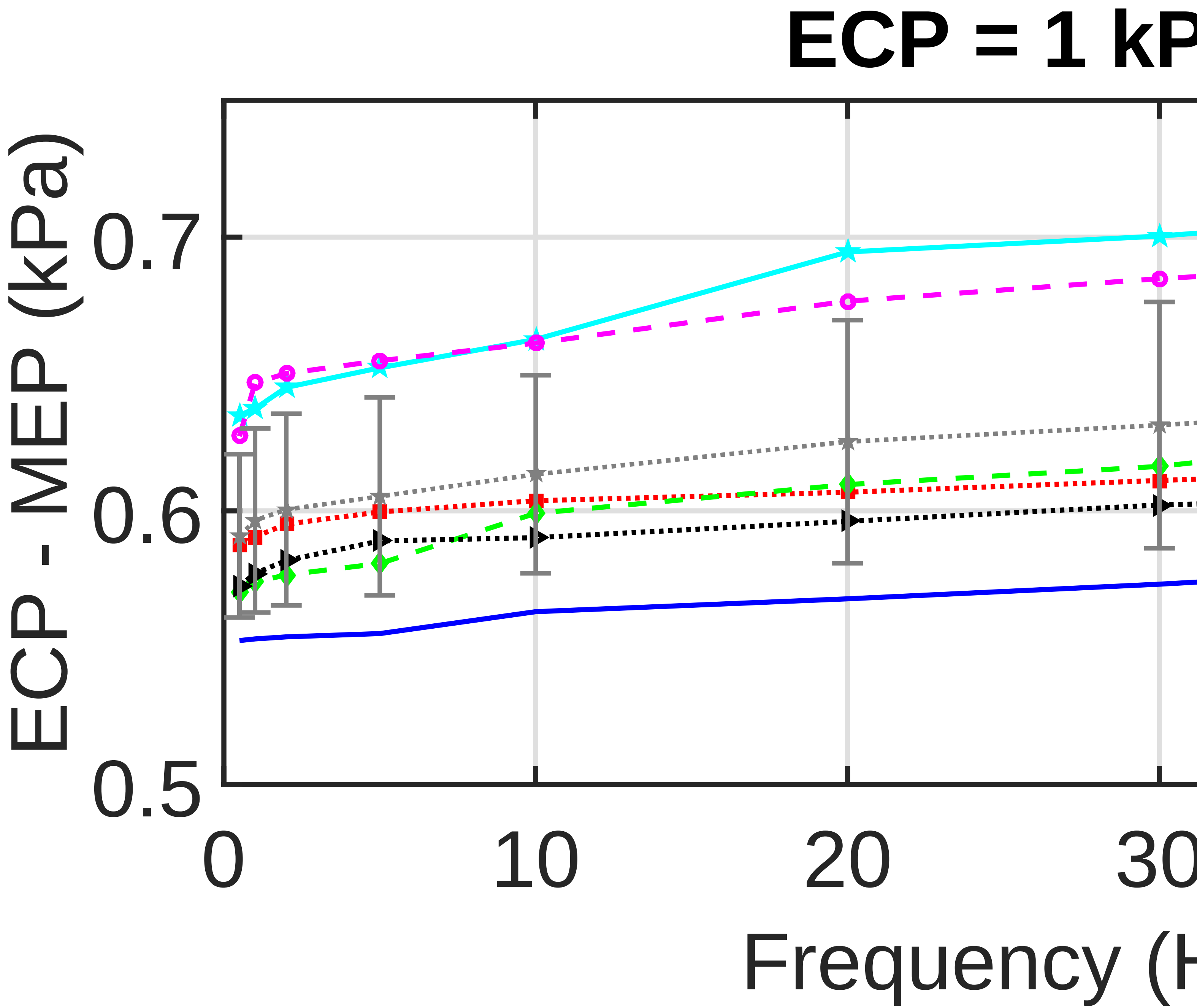


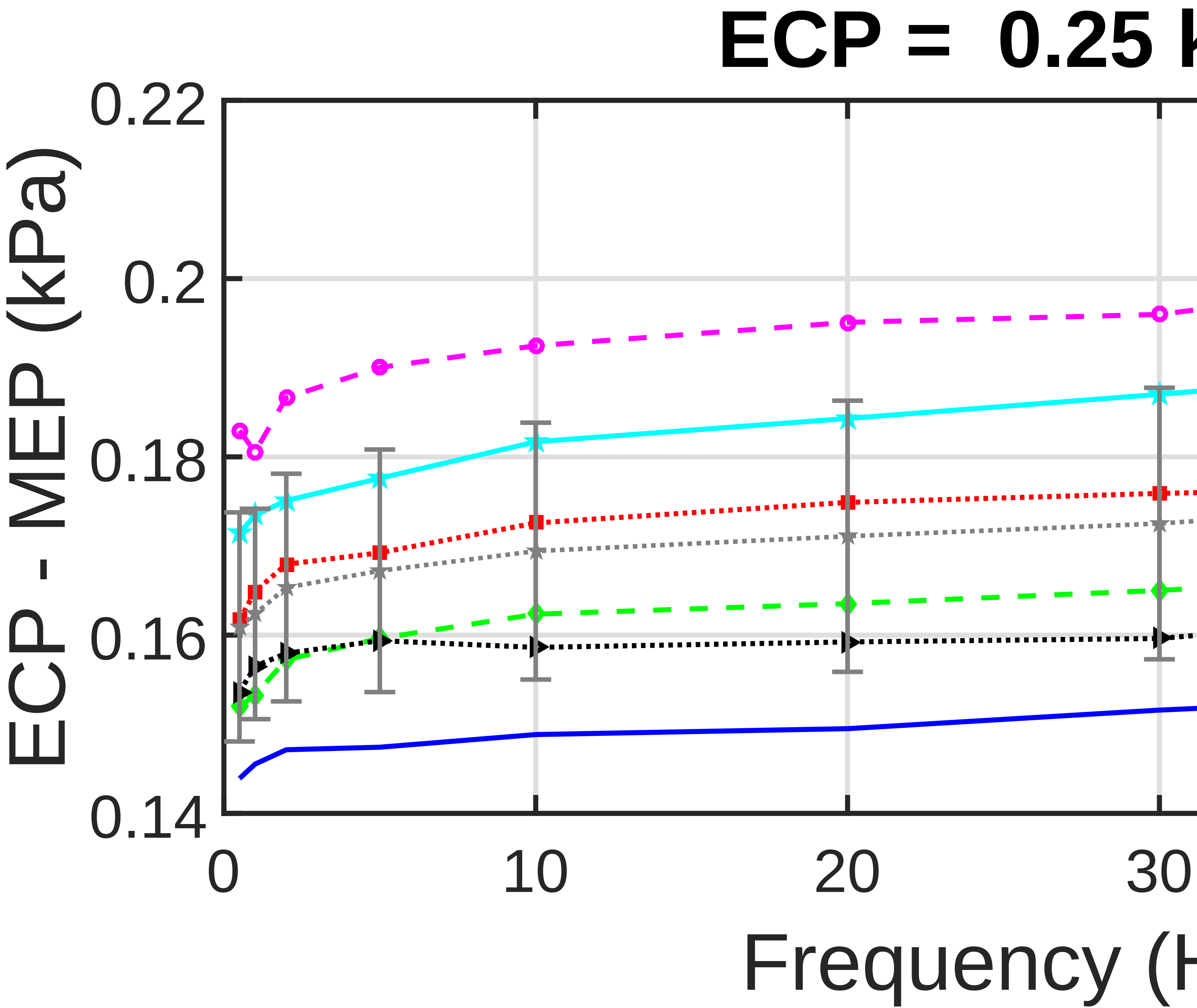

0.5 Hz
(a)
MEP (kPa)
0.5
0
-0.5
-1
-0.5
0
0.5
1
ECP (kPa)
10 Hz
(c)
MEP (kPa)
0.5
0
-0.5
-1
-0.5
0
0.5
1
ECP (kPa)


ECP = 0.25
R1
R2
R3
R4
R5
ECP - MEP (kPa)
0.3
0.2
0.1
0
10
20
30
Frequency (

SCRIPT




ECP = 1 kP
0.7
0.6
0.5
ECP - MEP (kPa)
0
10
20
30
Frequency (H


ECP = 0.25 k
0.22
0.2
0.18
0.16
0.14
ECP - MEP (kPa)
0
10
20
30
Frequency (H

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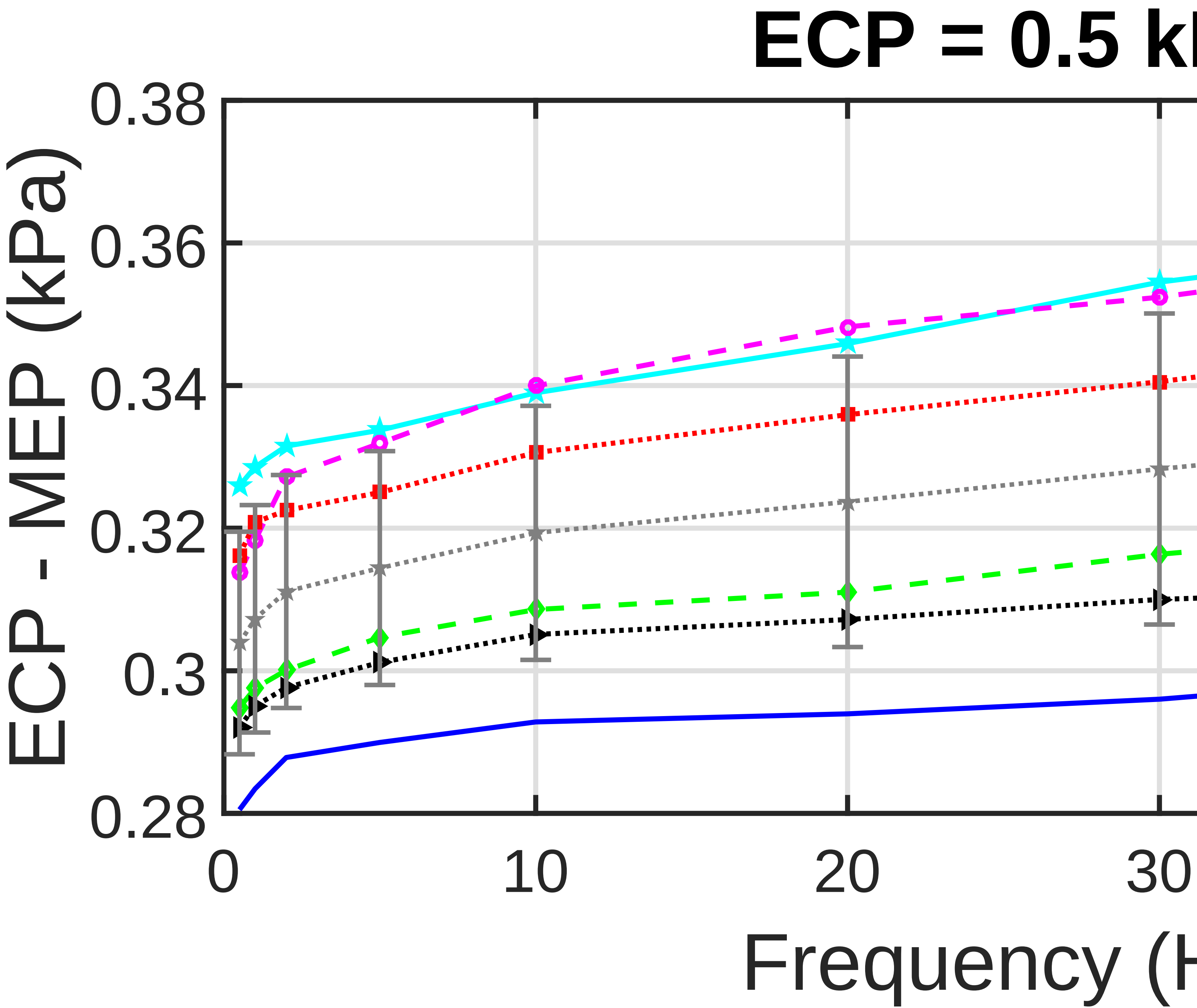

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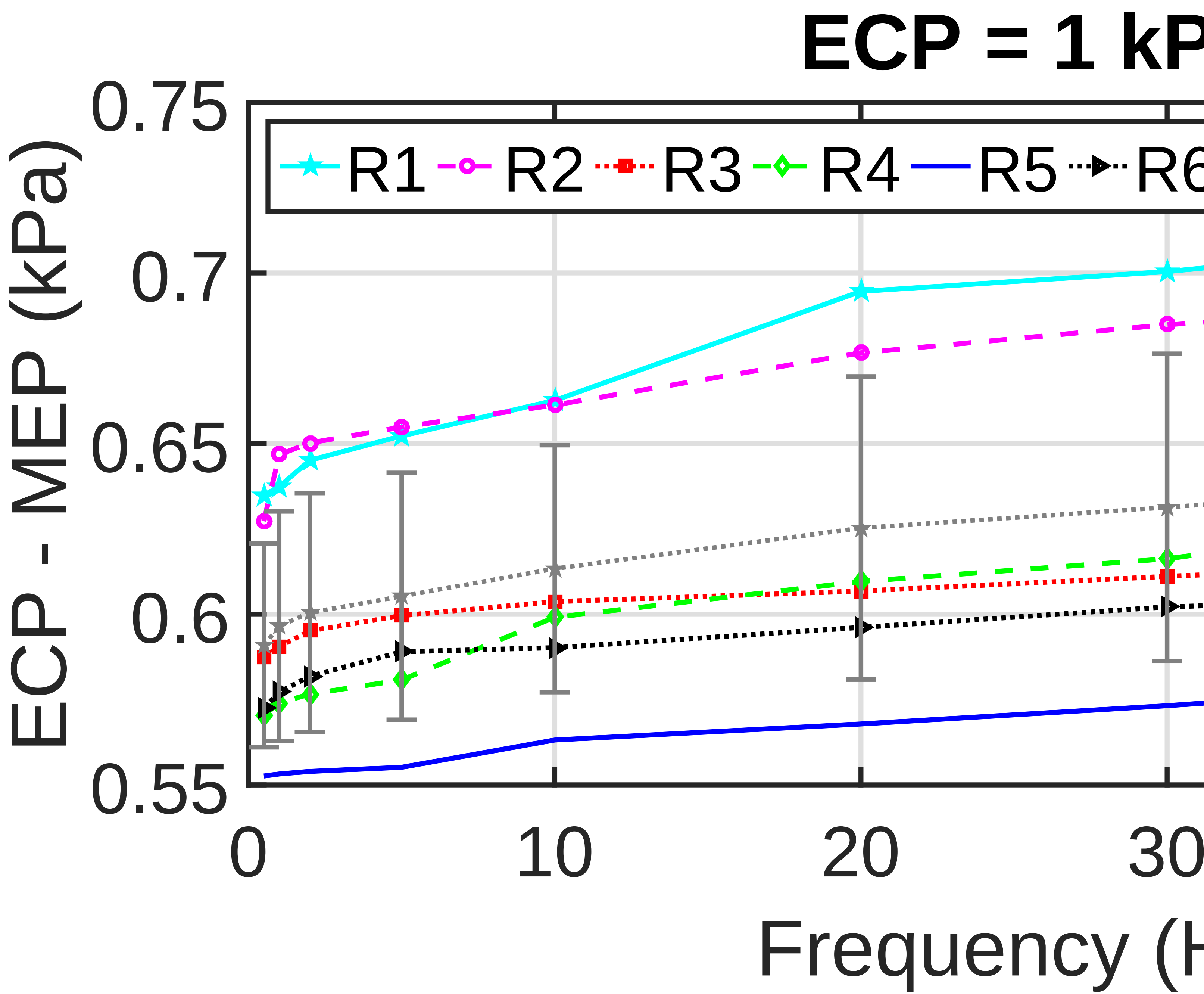

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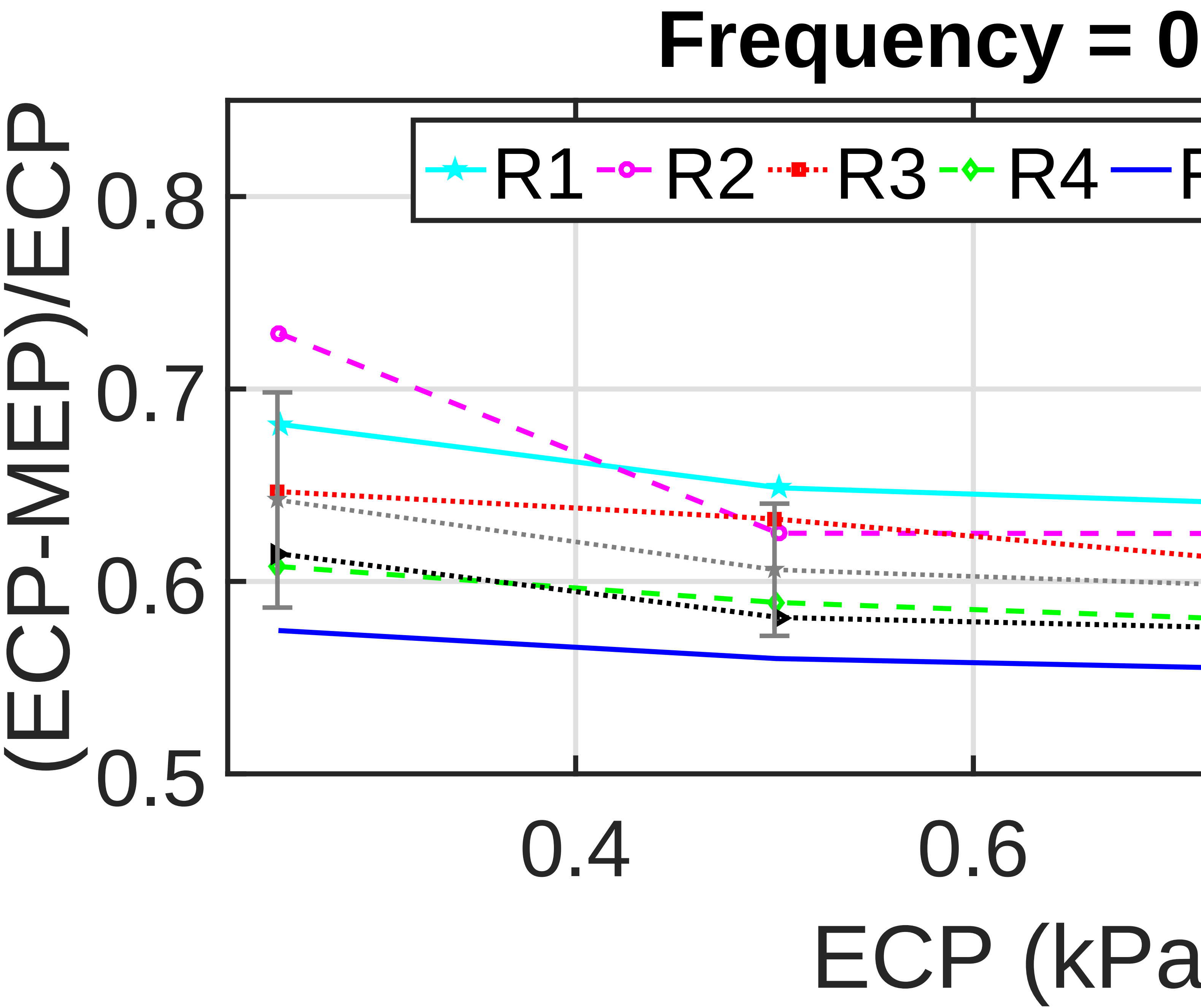

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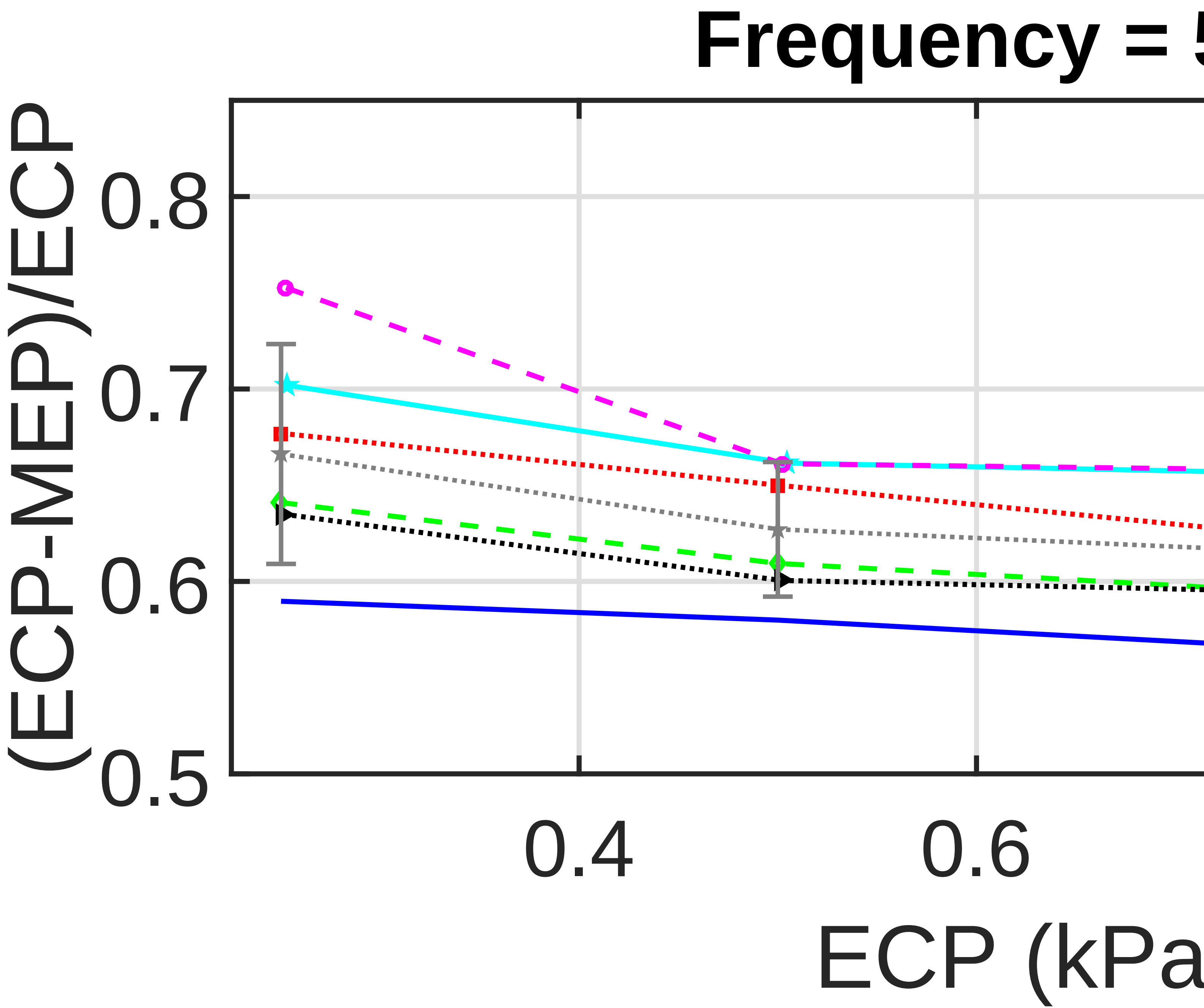

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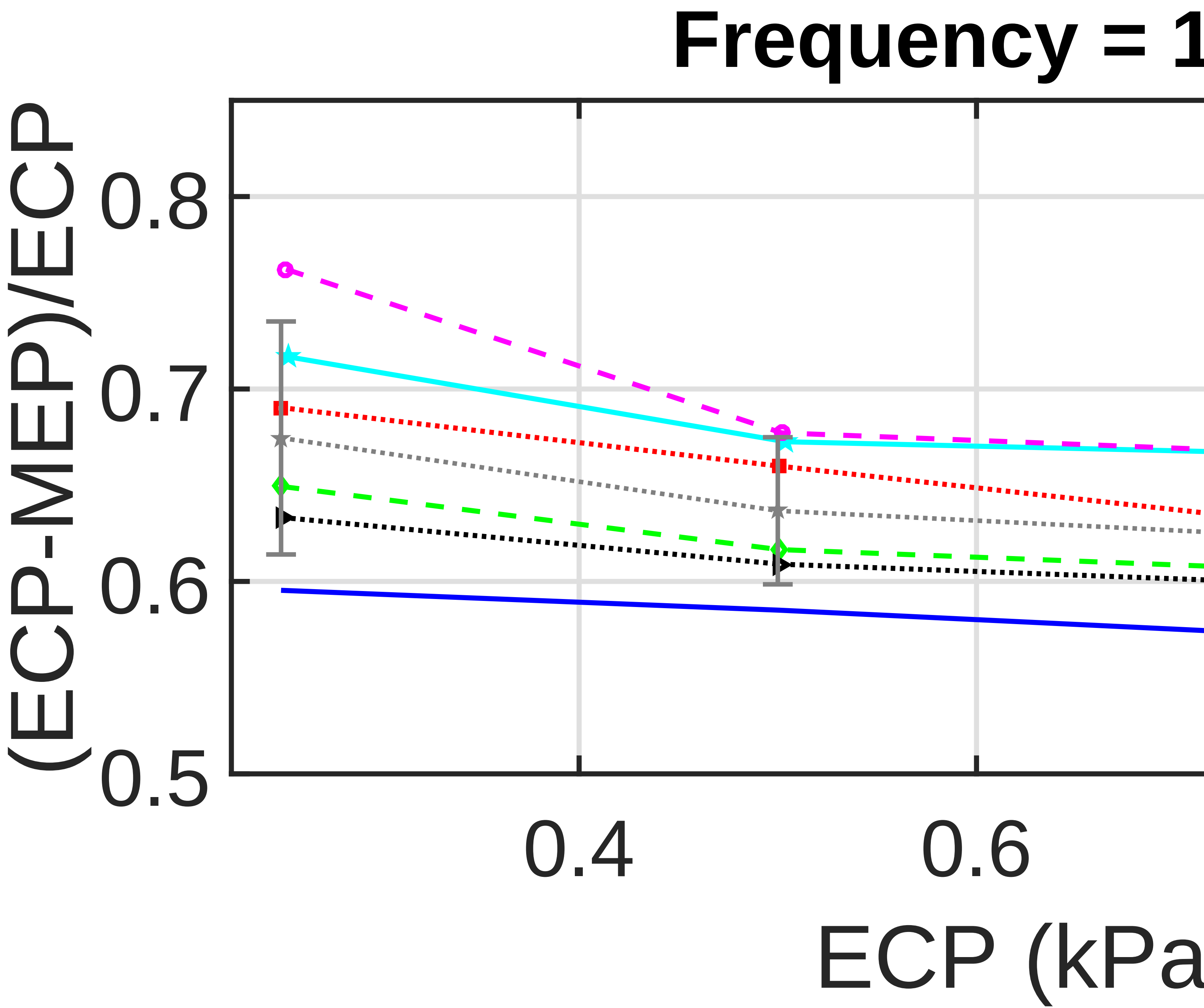

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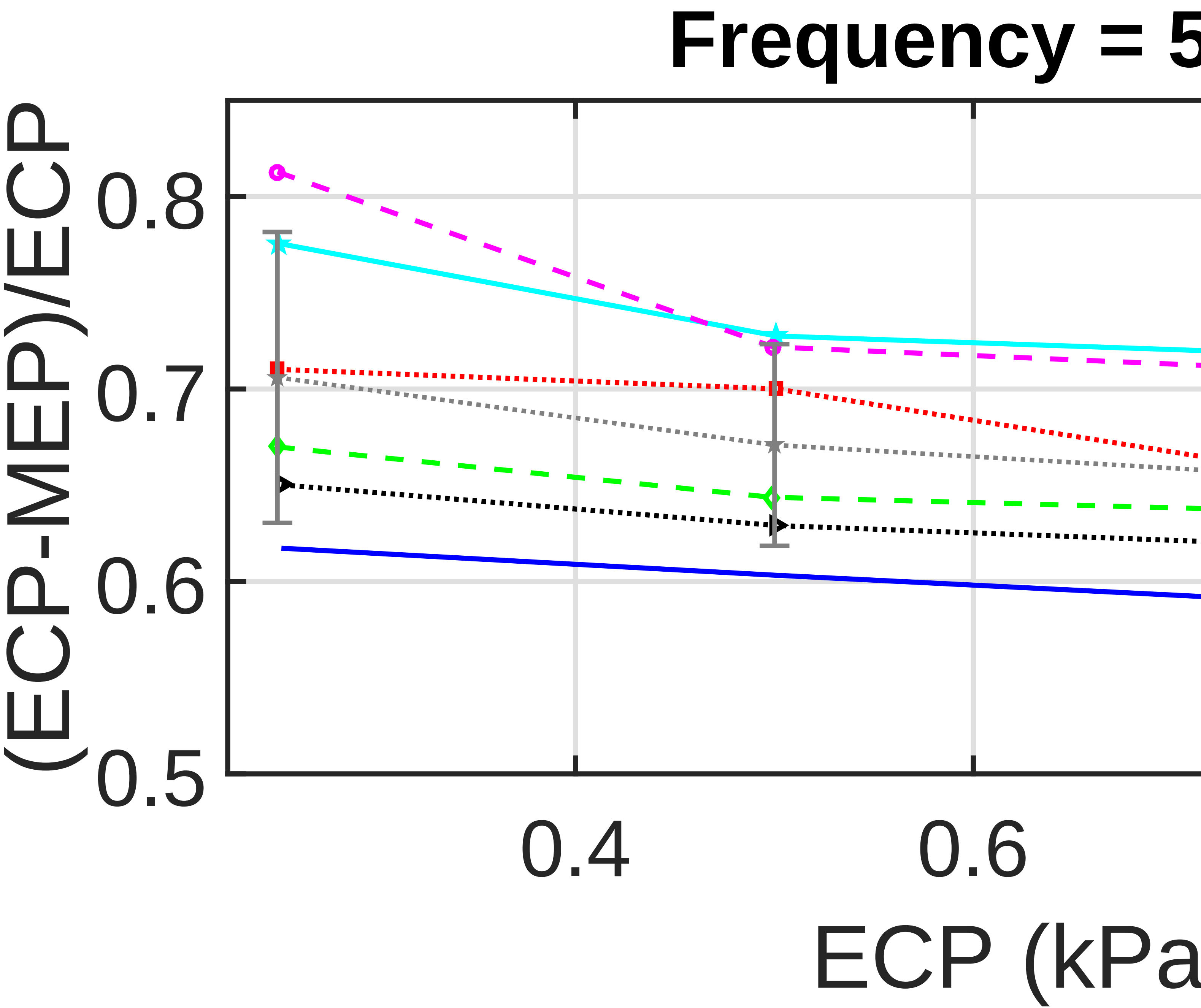
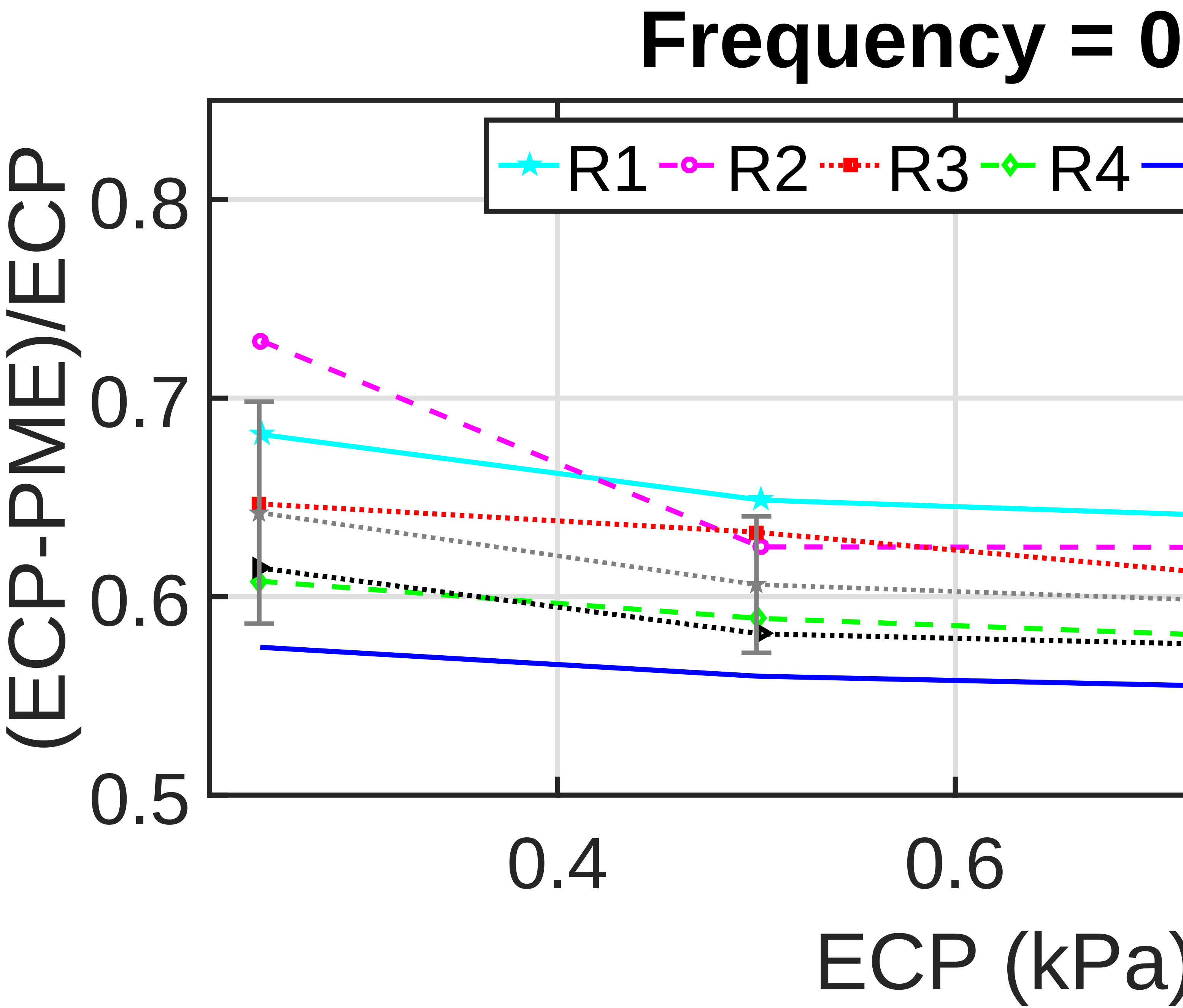
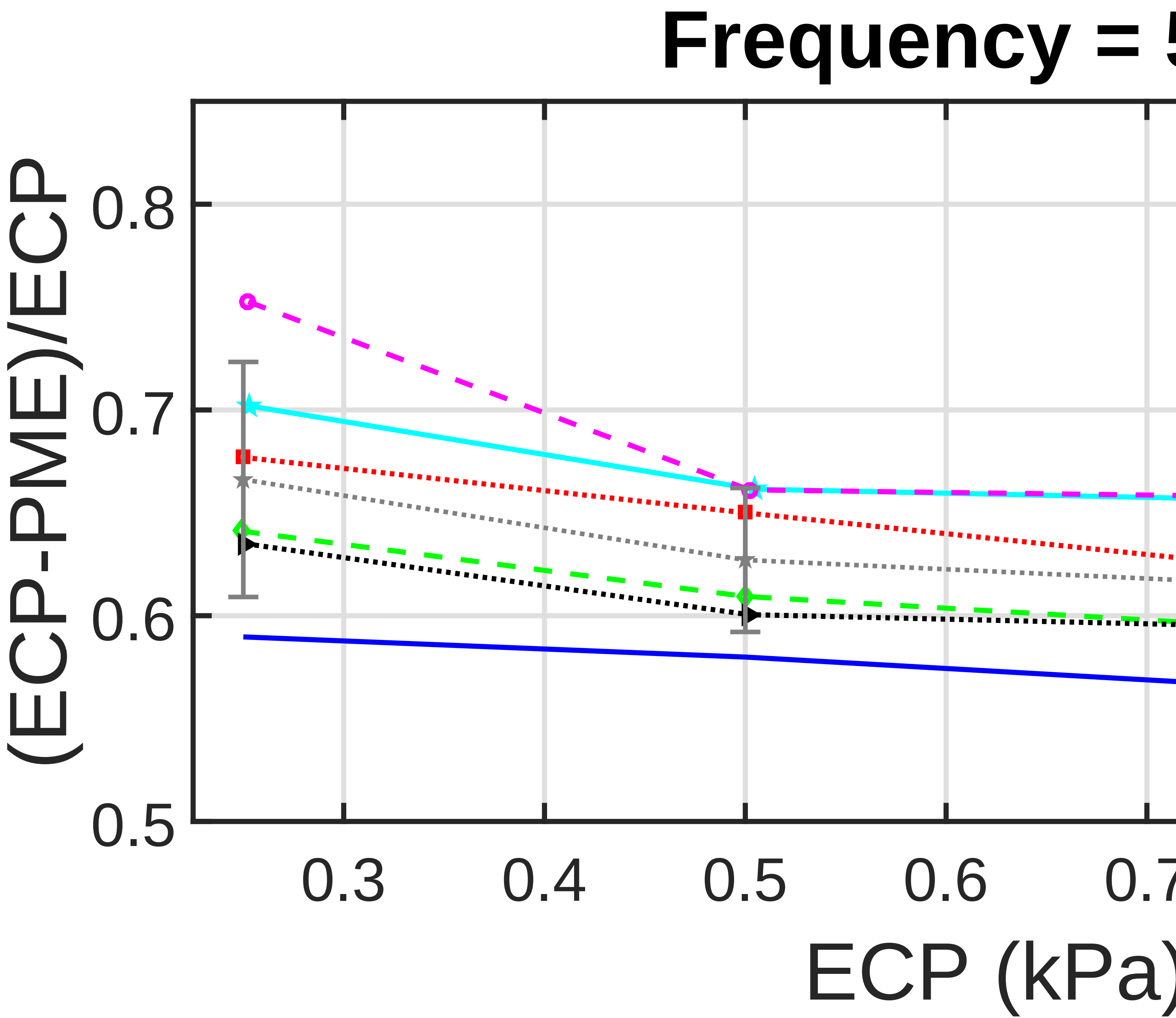
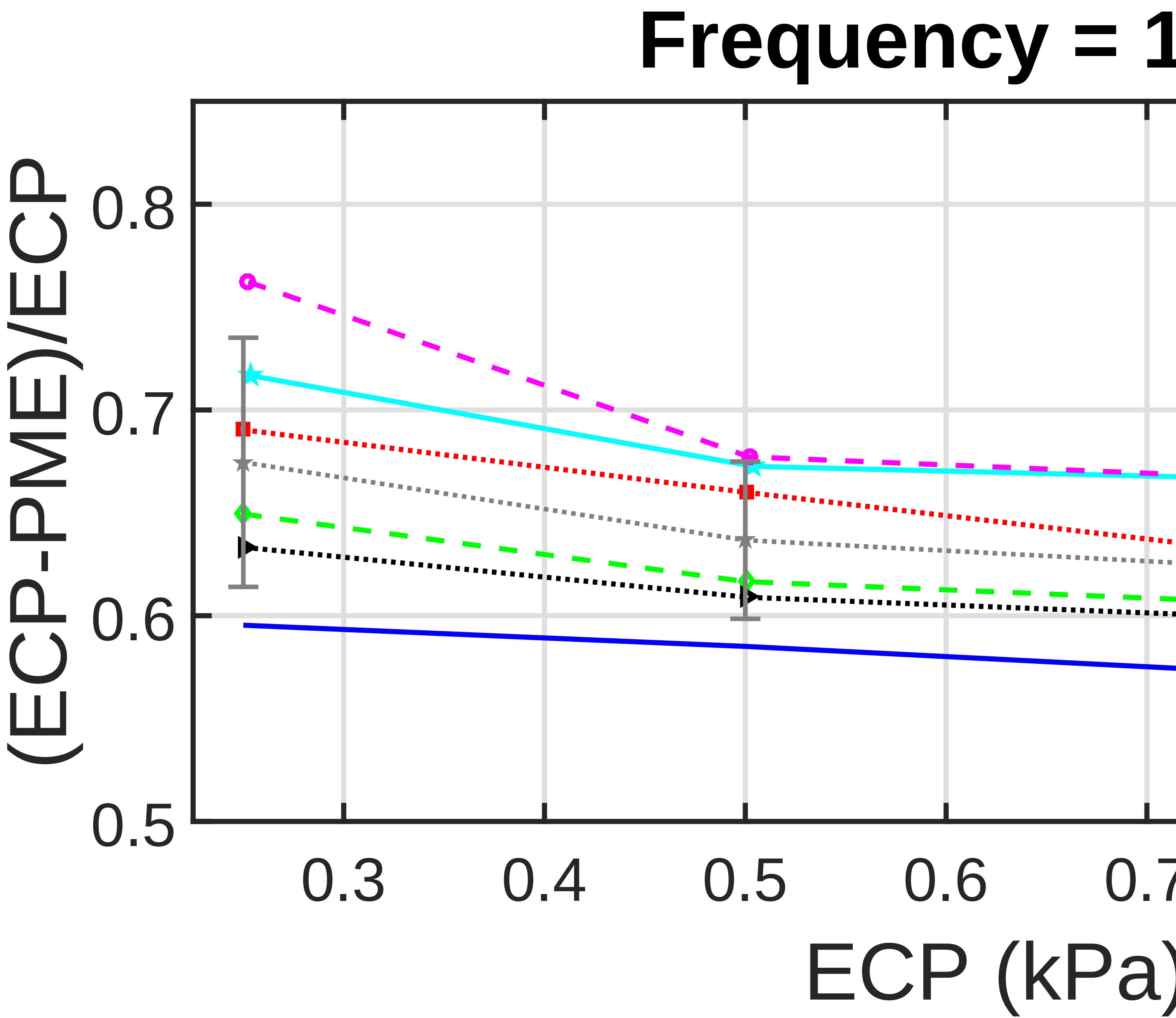




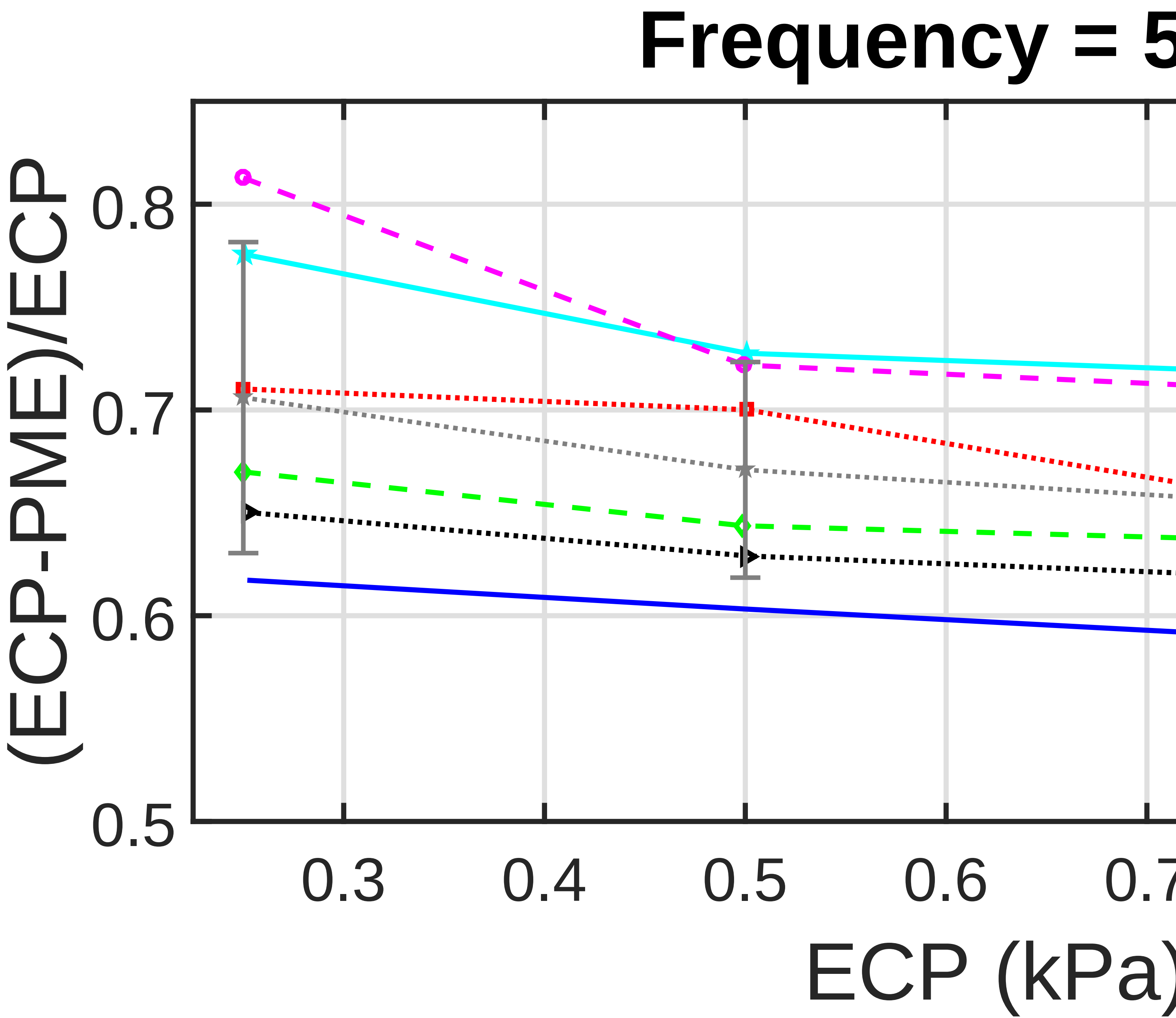
Frequency = 0
R1
R2
R3
R4
(ECP-PME)/ECP
0.8
0.7
0.6
0.5
0.4
0.6
ECP (kPa)



SCRIPT



Frequency = 1
(ECP-PME)/ECP
0.8
0.7
0.6
0.5
0.3
0.4
0.5
0.6
0.7
ECP (kPa)



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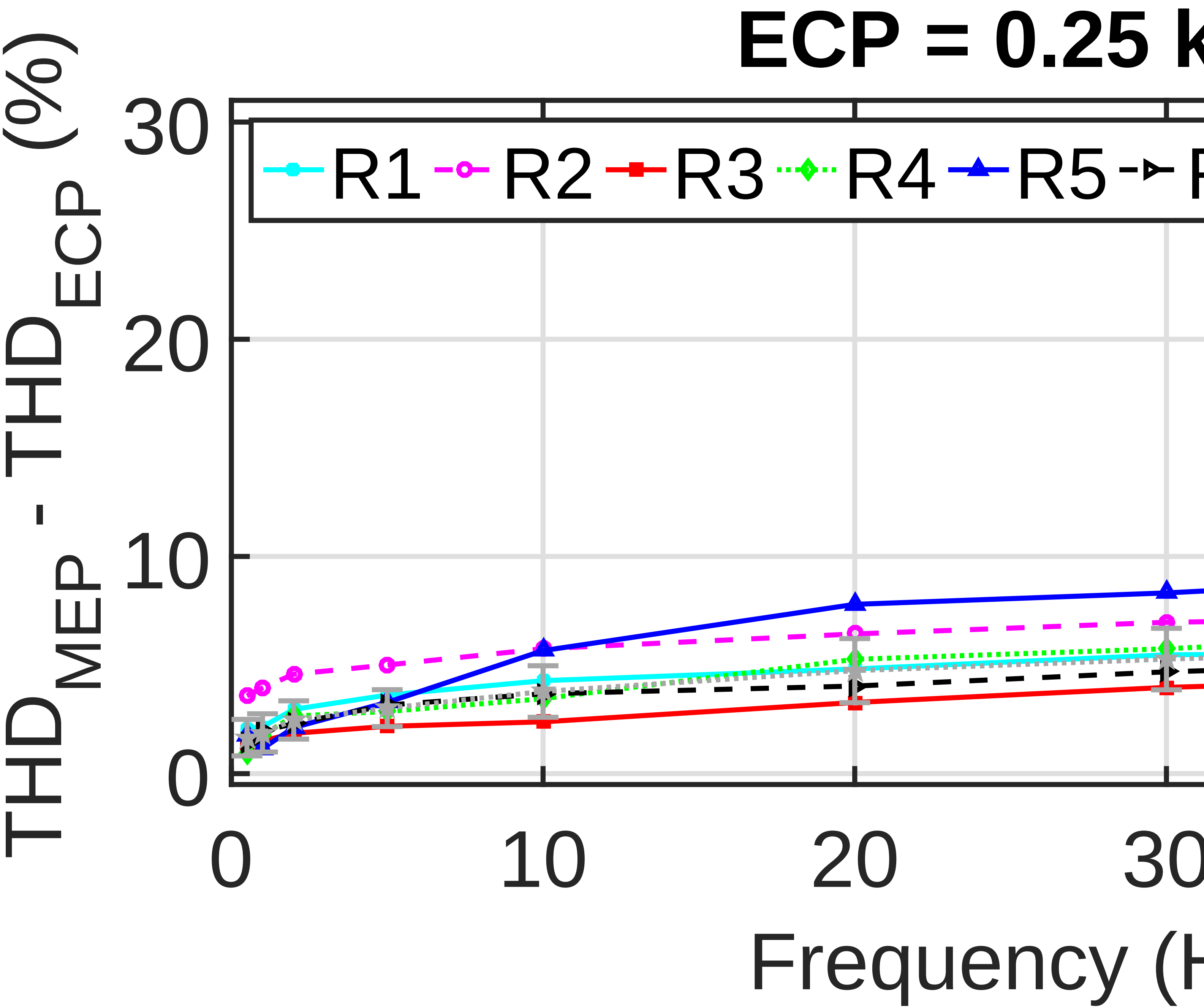

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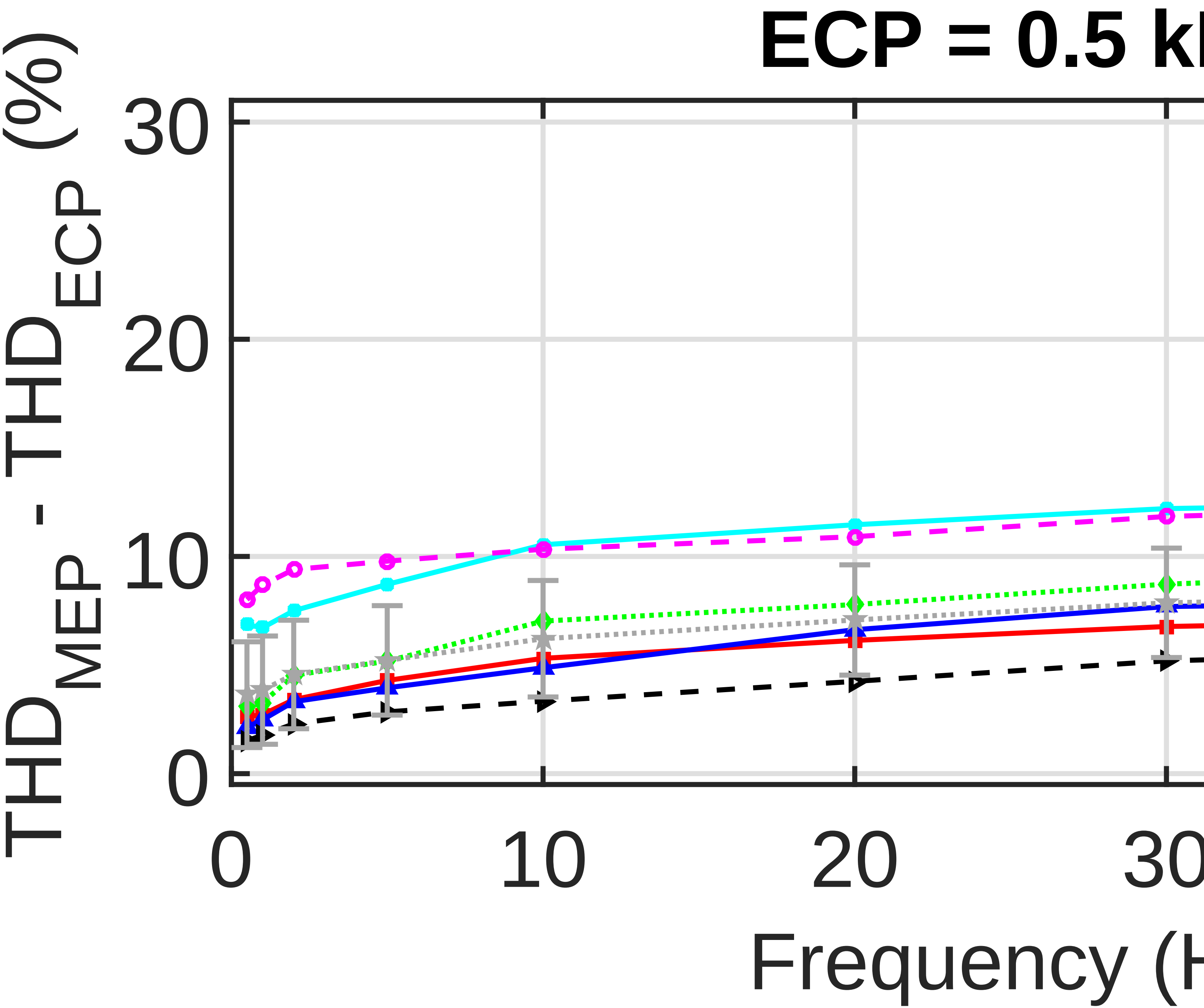

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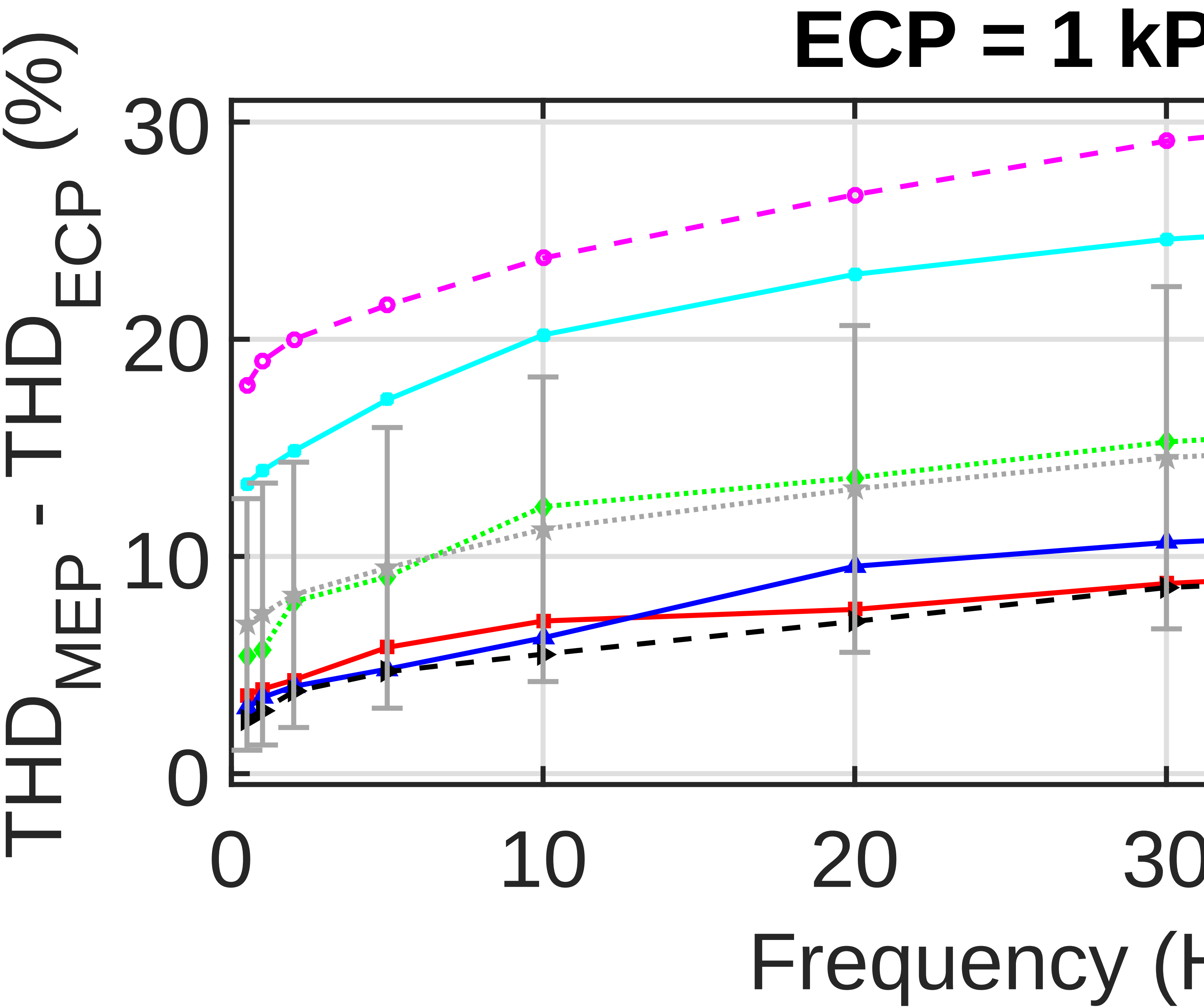
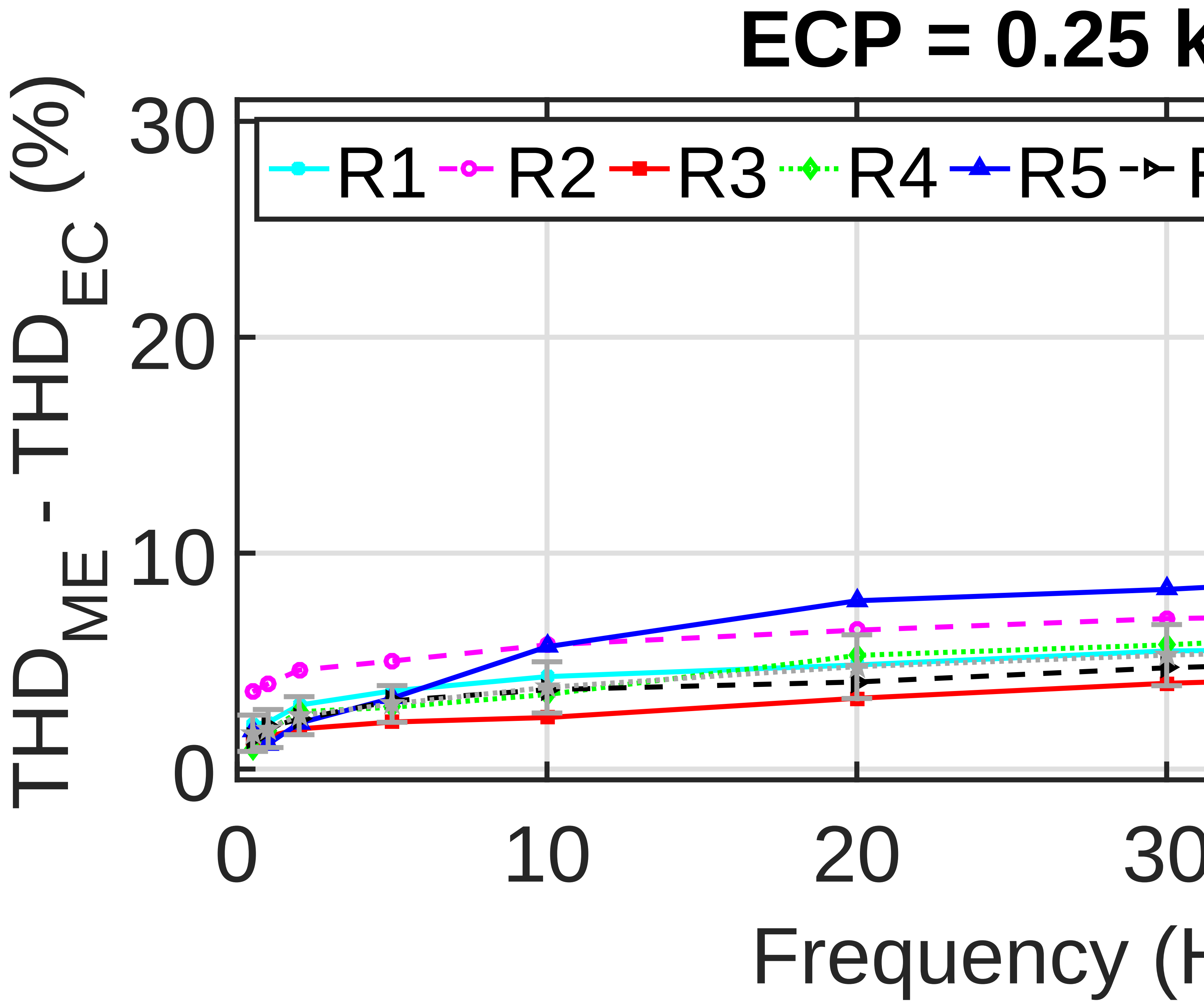
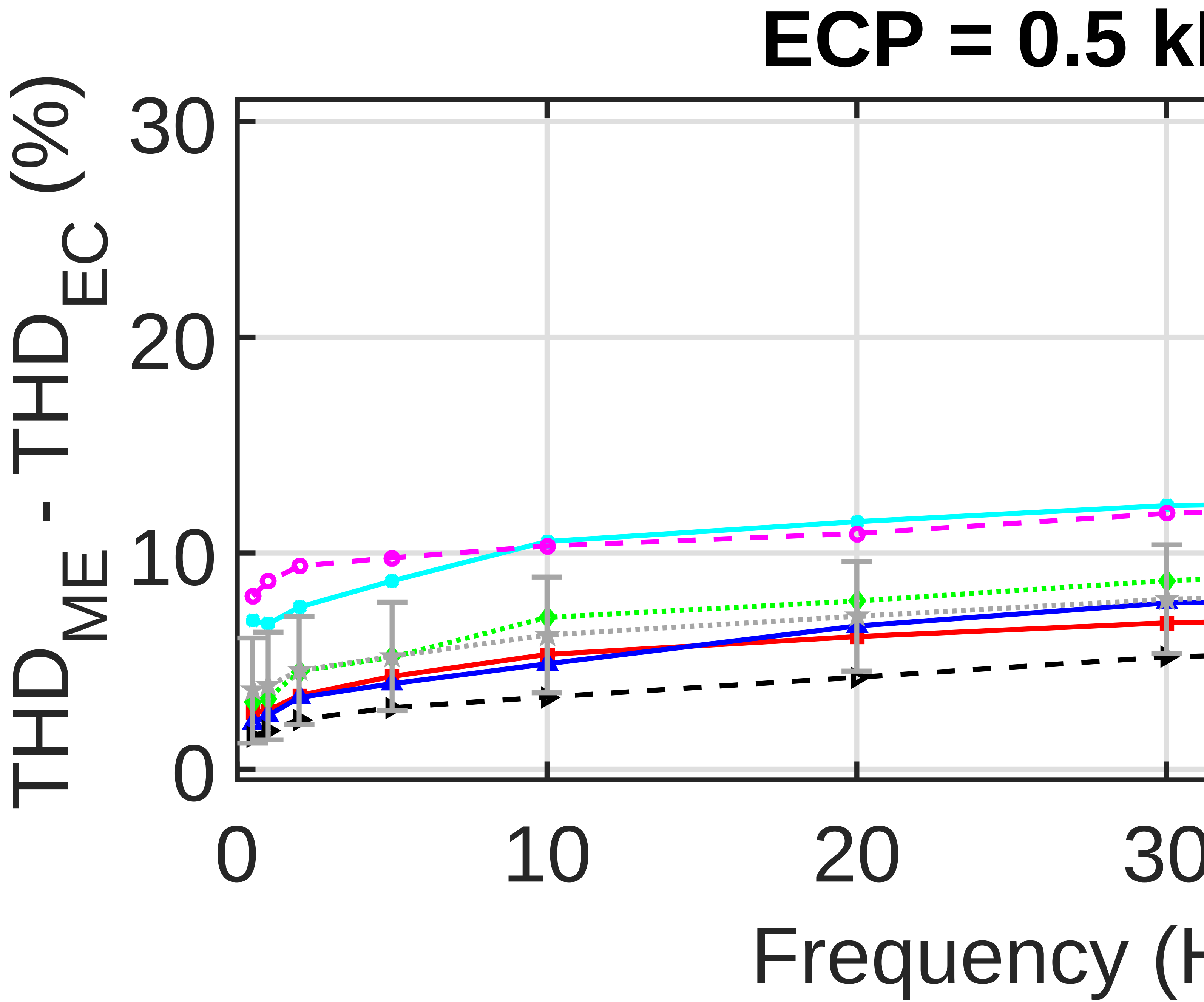




ECP = 0.25 k
R1
R2
R3
R4
R5
30
20
10
0
0
10
20
30
THD_ME - THD_EC (%)
Frequency (H

SCRIPT



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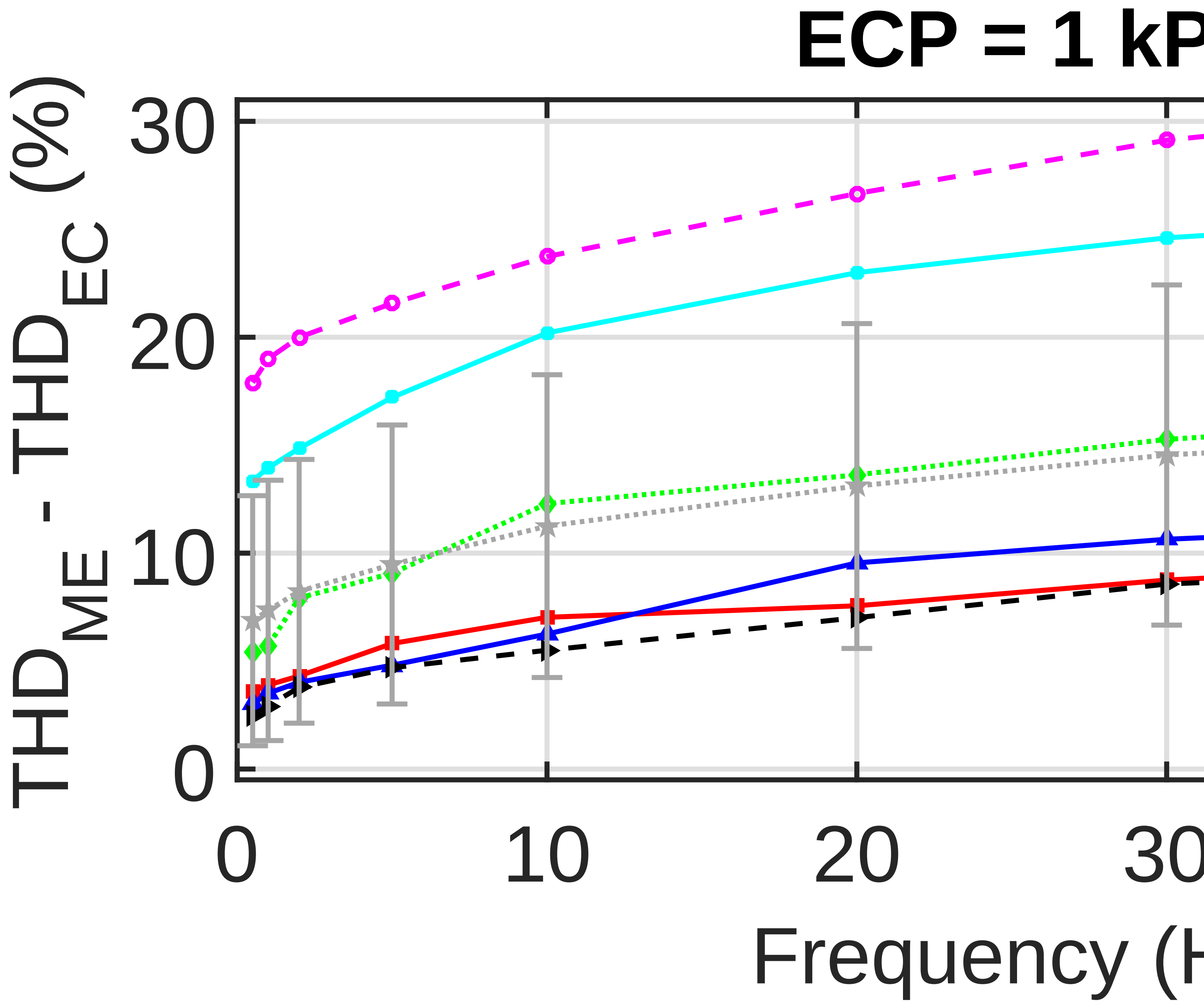

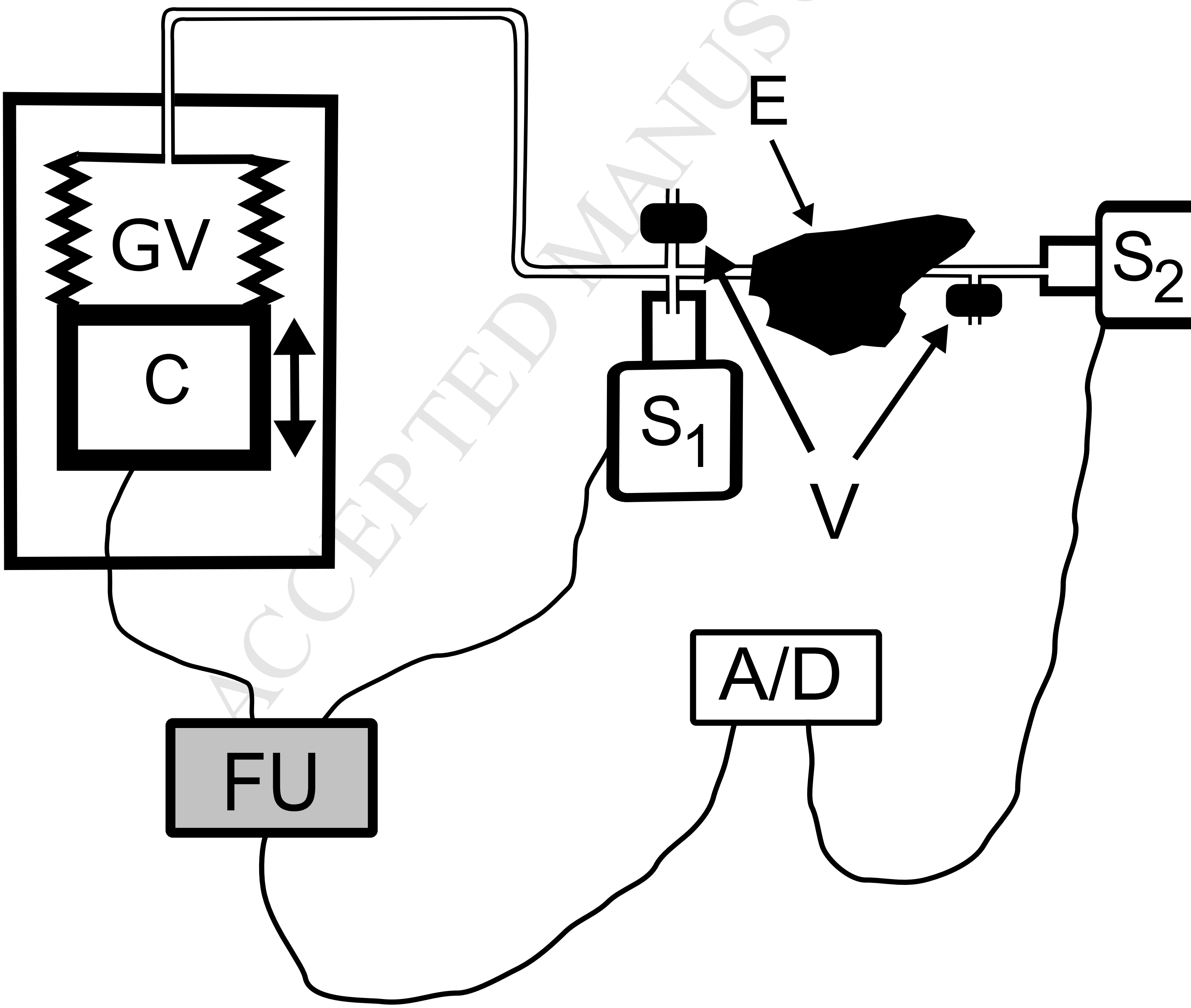
GV
C
E
S1
S2
V
A/D
FU

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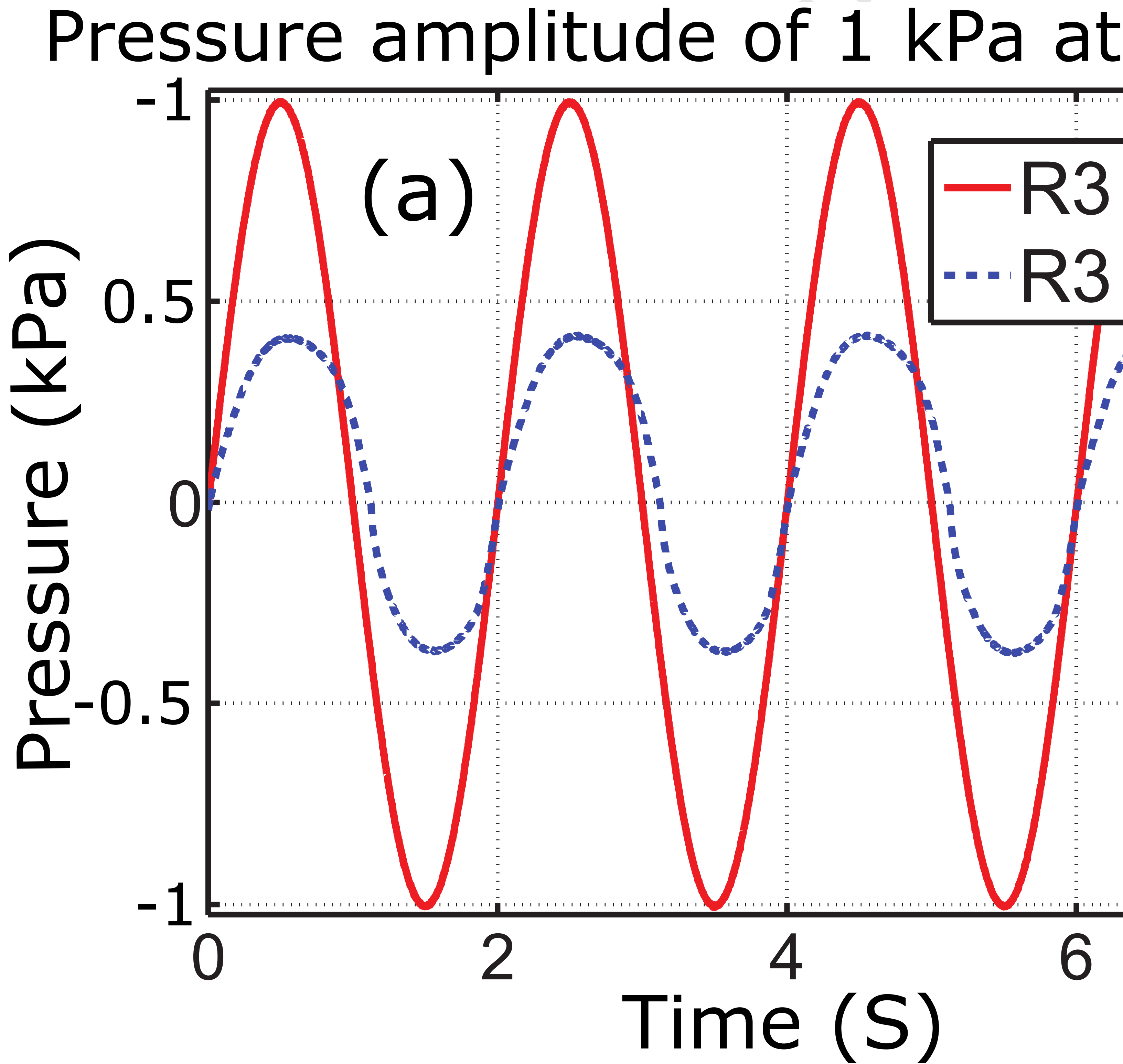

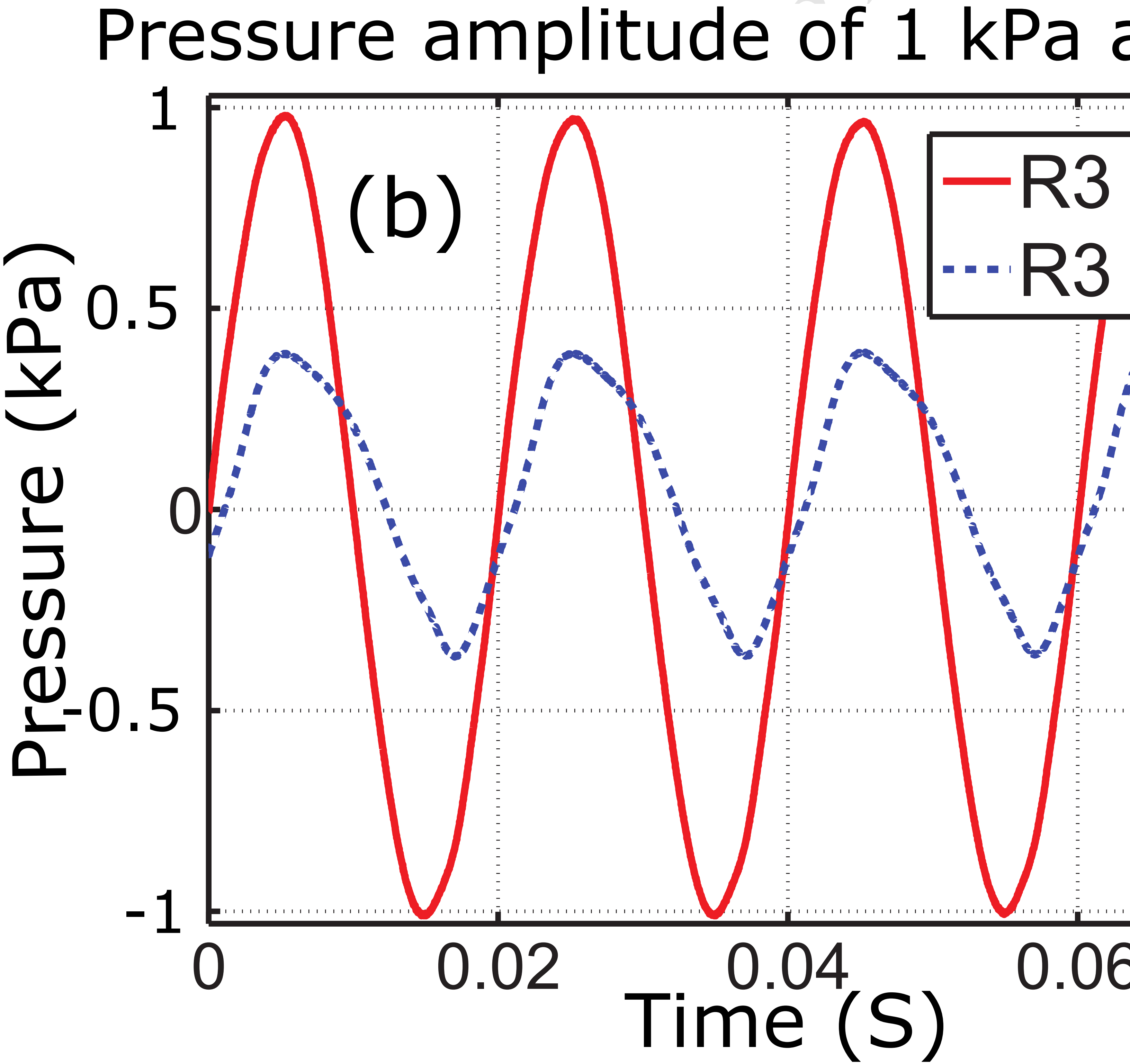
Pressure amplitude of 1 kPa a
(b)
R3
R3
Pressure (kPa)
1
0.5
0
-0.5
-1
0
0.02
0.04
0.06
Time (S)

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- Middle ear pressure in rabbit is measured as a function of sinusoidal varying ear canal pressure
- Pressure amplitudes from 0.5 kPa to 2 kPa, frequencies from 0.5 Hz to 50 Hz
- Trans-tympanic pressure increases as function of frequency
- Total harmonic distortion of middle ear pressure increases as function of frequency and amplitude

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