A Lag-Attentive Transfer-Entropy Bottleneck for Quantifying UA-FHR Coupling from Cardiotocography

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Background: Uterine contractions shape the intrapartum fetal heart-rate (FHR) response as persistent stressors that transiently interrupt uteroplacental blood flow. In healthy fetus the autonomic nervous system produces an FHR reaction to each uterine-pressure activity (UA), yielding high directed information from UA to FHR with coupling delay. As fetal condition deteriorates toward metabolic acidosis, this coupling changes: UA→FHR transfer- entropy dynamic changes and the delay lengthen.

Objectives: Develop a lag-aware surrogate of UA→FHR transfer entropy, embedded within a forecasting model. Explicitly model the UA→FHR lag that improves the clinical interpretability.

Methods**:** We propose **lag-attentive Transfer-Entropy-Bottleneck Variational-Autoencoder** that forecasts next two minutes of FHR_f, from wavelet-scattering and phase-harmonic features of past FHR_p and UA_p. The architecture has two causal pathways: **target-only conditional prior probability** $p(z|FHR_p)$ learned from FHR_p, and **source-conditioned posterior probability** $q(z|FHR_p, UA_p)$ that has access to UA_p where $\boldsymbol{z}$ is the latent representation. Between them there is a **causal lag cross-attention module:** the current target state acts as a query over a bounded memory of past UA states, producing an attention distribution over lags. FHR_f is decoded as a baseline forecast from FHR_p plus a UA-driven residual from the stochastic latent, forcing the bottleneck to encode UA-specific information beyond FHR_p. The KL divergence between posterior and prior gives a per-timestep upper bound on transfer-entropy, measuring the extra contribution of UA_p to FHR_f conditioned on FHR_p.

Results: Figure-1 illustrates an HIE case where clinically, longer UA→FHR coupling delays are expected. Two observations emerge directly from the learned attention: 1) The UA history that contributes to the latent bottleneck is concentrated within the most recent two minutes; 2) lag-scaled TE surface is episodic with discrete bursts rather than tonic.

Conclusion: The model unifies two key aspects of UA→FHR coupling, **how much** information flows and **at what delay**, into single output of Transfer-Entropy-Bottleneck.

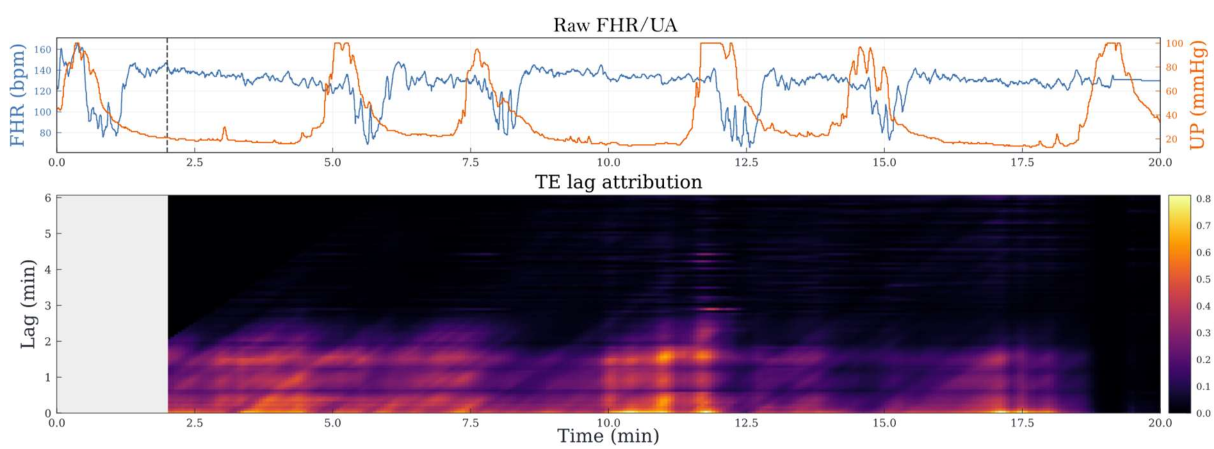

Figure 1: Temporally aligned intrapartum 20-minute epoch (2 hours before delivery) of FHR and UA (top) and transfer-entropy attribution, weighted by causal cross-attention over past UA lags (bottom). Brighter colors associated with higher directed information from past UP at each lag to future FHR at time t. Information transfer appears as discrete episodes with mass concentrated below two minutes of lag. Grey shaded strip indicates warmup period.