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➤ Quantitative sodium MRI in foods: addressing sensitivity issues using single quantum Chemical Shift Imaging at high field

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NMR platform for agronomy, food science and nutrition

➤ ^{23}Na MRI, a good tool for food science

MRI allows to achieve 3 key parameters

○ **Nucleus density**

- Technological food properties (sanitary issues, public health ...)
- Numerical modelling → optimize processes

○ **Localisation**

→ Salting process = heterogeneous process:

- Diffusion from surface to center
- Food intrinsic heterogeneities = salt barriers

→ Control of sensory properties:

- salt heterogeneity enhances saltiness

○ **Nucleus/matrix interaction**

- Na^+ release drives saltiness perception
- Technological properties ? Salt diffusion?



Heterogeneous salt distribution in hot snacks enhances saltiness without loss of acceptability

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Non-destructive: longitudinal following of processes, no inter products variability bias

➤ ^{23}Na MRI is not easy

Two main constrains: sensitivity and relaxation

Food products [salt] \approx 100mM to 800mM

Spatial resolution needed \approx 1-x mm

Temporal resolution needed \approx depends on the process

Rice cooking = 10 minutes

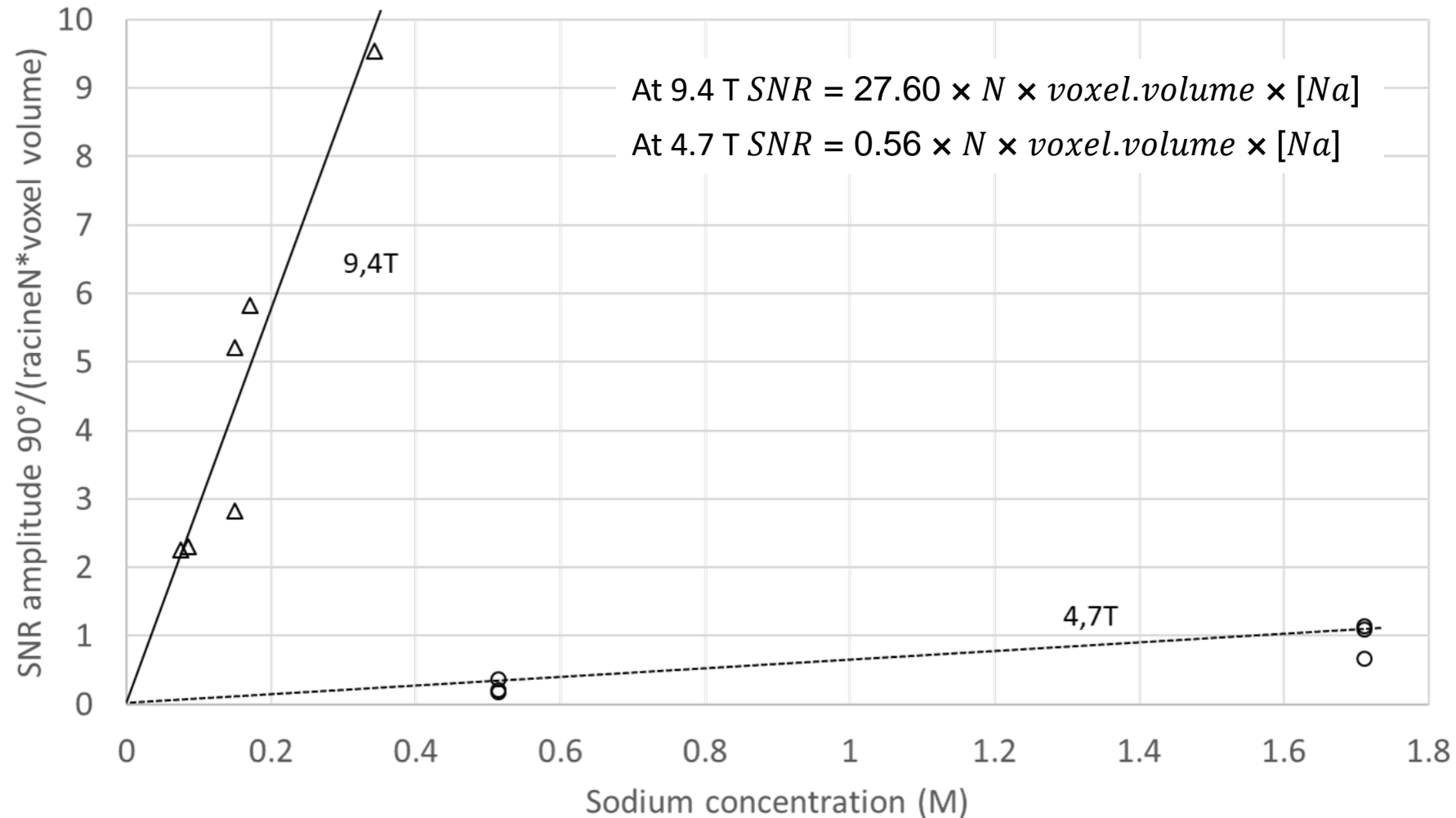
Ham drying = 9 months

Is it possible to see sodium repartition in my [choose a food product] during the [choose a food process]?

“It depends” is not a satisfactory response → abacus

➤ ^{23}Na MRI is not easy

Two main constrains: sensitivity and relaxation



0.17 M

9.4 T MRI device

1 mm³

SNR=10

1h16 total acquisition duration



0.17 M

9.4 T MRI device

0.5x0.5x1 mm³

SNR=10

4h50 total acquisition duration

Experimental designs

In our given experimental conditions
(coil, filling ratio ...)

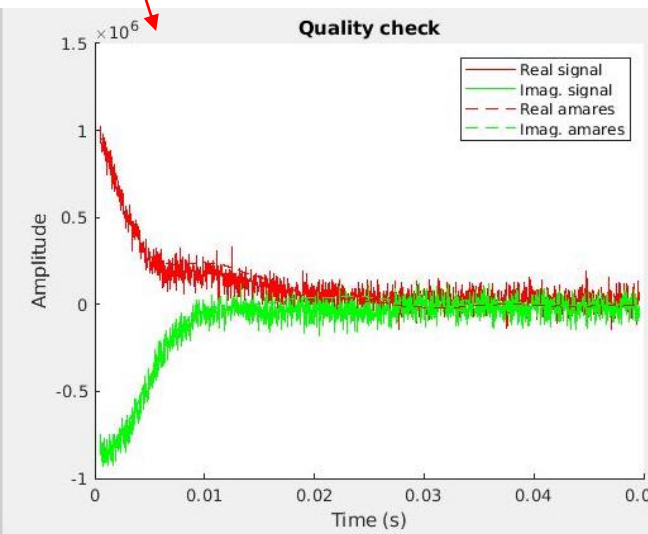
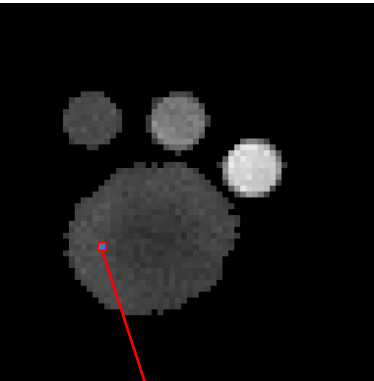
➤ ^{23}Na MRI is not easy

Two main constrains: sensitivity and relaxation

Nucleus	Spin (I)	Sensitivity/ ^1H	γ ($10^7 \text{ rad T}^{-1}\text{s}^{-1}$)	Resonance (MHz) à 4,7T	Resonance (MHz) à 9,4T	Resonance (MHz) à 11,7T
^1H	1/2	1	26,75	200	400	500
^{23}Na	3/2	0,0925	7,08	53	106	132

- Possible quadripolar interaction → Multi exponential NMR signal decay?
- Short T_2^* → Need to correct sodium NMR signal lost in fast relaxation.
- Short T_1 → Save time thanks to short repetition time

➤ Our MRI solution: Chemical Shift Imaging (CSI) sequence



Spectroscopic imaging:
one pixel = one full FID

By adjusting the experimental FID

1. We can extrapolate the amplitude well before the echo time
2. We access the B_0 variations, locally, in each pixel
3. We access the T_2^* value, locally, for each pixel

Because CSI is a cartesian filling sequence, there are no relation between relaxation and resolution. Localization is not biased.

We wanted

- Nucleus density ✓
- Localisation ✓
- Interactions ✓

We had to manage

- Poor sensitivity ✓
- Fast relaxation ✓

➤ M&M: the food products

Two very different real food products in terms of **salt content**, **size** and **tissu type**.

Cooked carrot



Peeled carrot

Cylinder length 80 mm x diam. 20 mm

Cooked 25 minutes in boiling salted water (171mM)

Reference tubes: 85, 171 and 342 mM of NaCl in gelatin from porcine skin

Norwegian dry cured ham



Entire Norwegian dry cured ham

End of process, 9 months drying

Length 33 cm x width 12 cm x height 8 cm

Reference tubes: 2x513 and 2x1710 mM of NaCl in gelatin from porcine skin

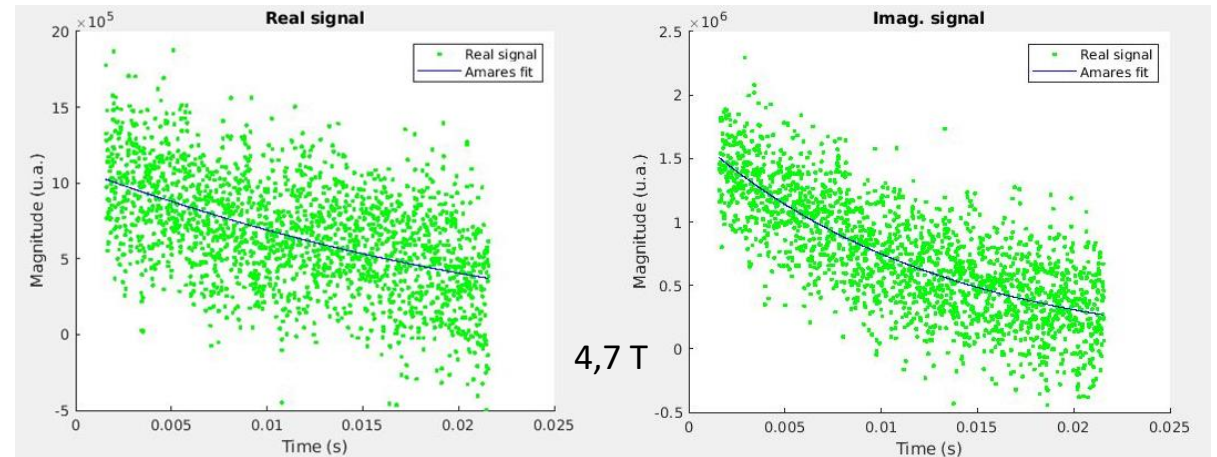
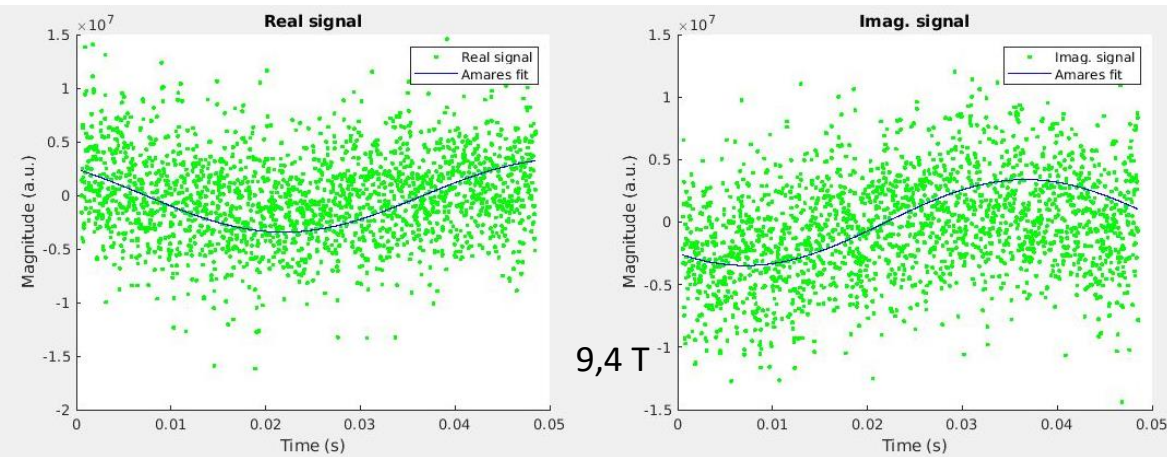
➤ M&M: 2D CSI parameters and adjustments

CSI parameters

B0 (T)	Object	In plane vox. size (mm)	Matrix size	Slice thickness (mm)	FID Nb points Temporal resol. (μs)/duration (ms)	TE/TR (ms/ms)	Total duration
9.4	Carrot and tubes	0.5*0.5	64 x 64	8	4096/12/49	0.95/500	1h30
4.7	Ham and tubes	2*2	64 x 64	8	8192/5/41	5.4/200	2h15

Adjustment

Voxel wise adjustment is done in the frequency domain with a single Lorentzian peak.



A, T2*, B0



Amplitude = [Na] independent of T2*, B0

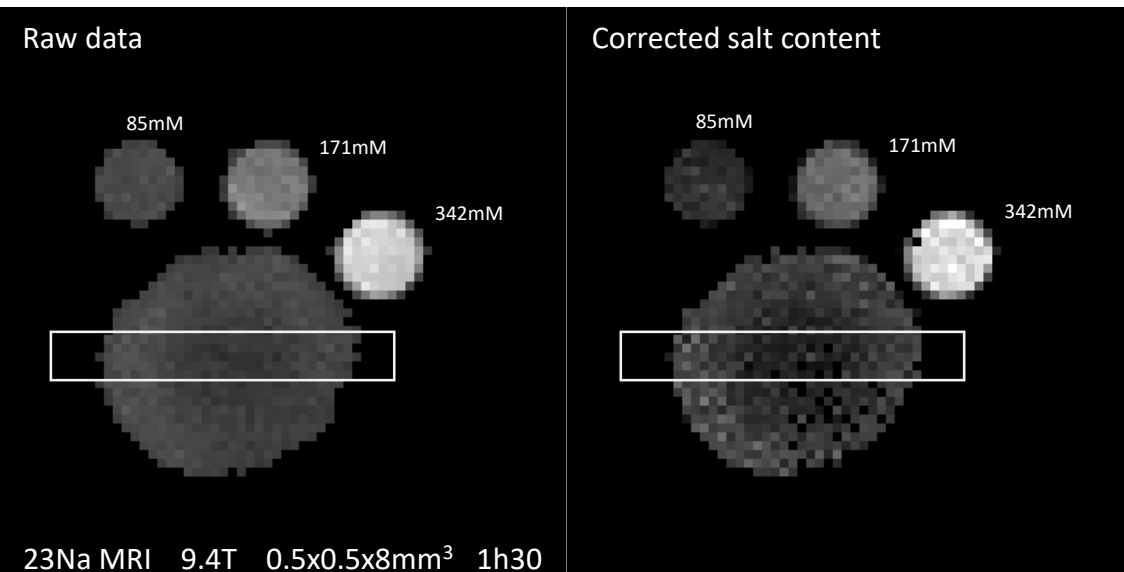


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Sodium MRI in food

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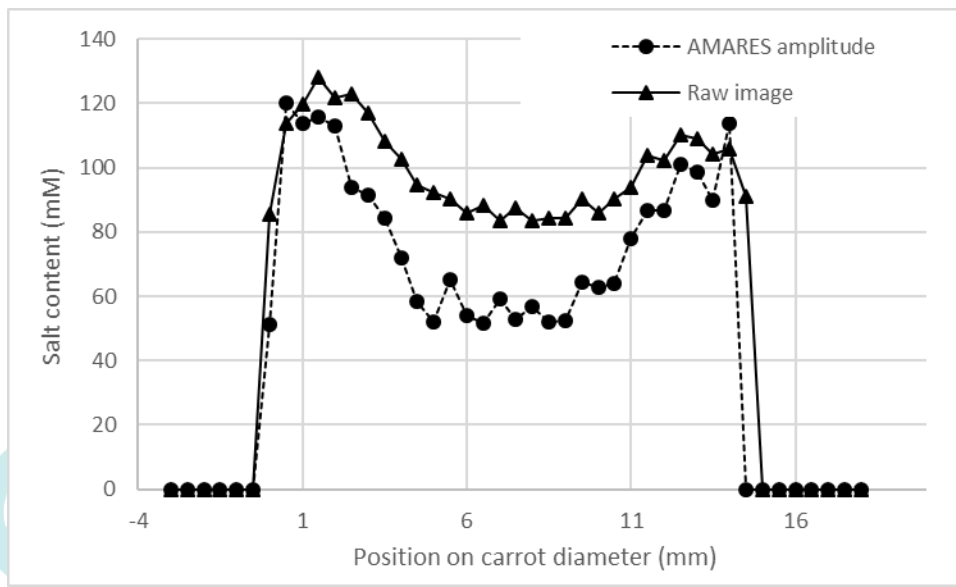
➤ Results: salt gradient in the cooked carrot



- Salt content decreases from the edge to the center
- Maximum salt content (120mM) is coherent with the $[Na]=171mM$ in the boiling water
- Correction enhances the gradient

Because relaxation differences between the center and the edge (salt, tissue...)

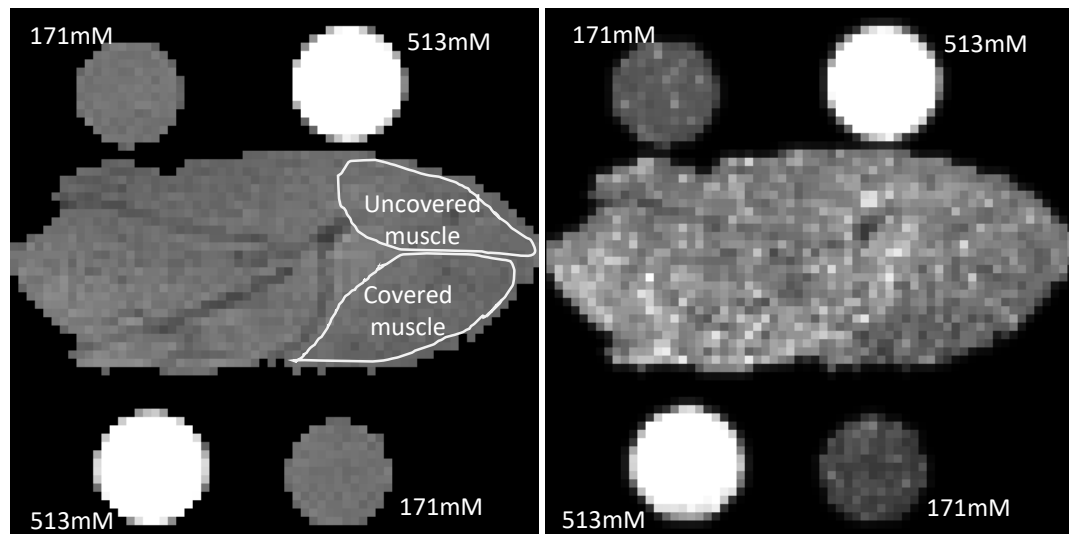
Relaxation must be corrected to access sodium map independent to local relaxation properties



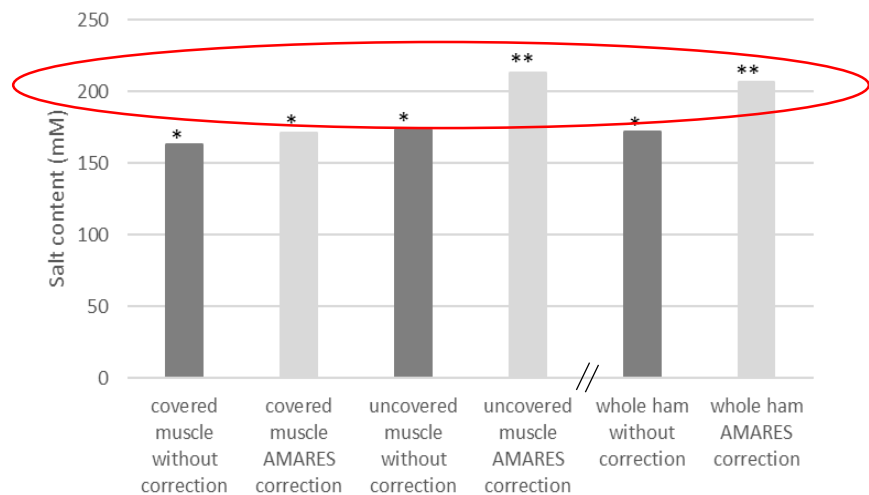
➤ Results: different salt content in different ham muscles

Raw data

Corrected salt content



23Na MRI 4.7T 2x2x8mm³ 2h15



- Before correction no difference
- After correction covered muscle [Na] < uncovered muscle [Na]
- Relaxation correction significantly enhances the whole ham salt content

Relaxation must be corrected to access sodium map independent to local relaxation properties

[Na] ≈ 200mM << real [Na] ≈ 800mM

Adjustment = mono exponential decay, if bi exponential decay 3/5 of the signal is not visible

Correction : [Na]=200mM*5/2=**500mM** ... still far away

More complicated: **Nour El Sabbagh** showed a mix of relaxation behaviours in food products



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➤ Perspectives, quantitative sodium MRI improvement

1. Taken into account all relaxation behaviors
2. b_1+ inhomogeneities correction

Why?

1. High fields increases these inhomogeneities (because spatial wavelengths shortens)
2. Salt causes conduction lost → local lost of excitation power (b_1+ inhomogeneities)
3. Reference tubes are often placed close to the coil, where inhomogeneities are high

How?

Double Angle Method CSI protocole at 90° and 30°

Double the total acquisition time

Introduce propagated noise from the 30° ^{23}Na MRI





Cost/benefit ratio

> Perspectives, application to food science and health



Inhomogeneous spatial distribution of NaCl → saltiness enhancement

Contents lists available at [SciVerse ScienceDirect](https://www.sciencedirect.com)
 Food Research International
 journal homepage: www.elsevier.com/locate/foodres

 	MRI/NMR	Sensory evaluation <i>in vivo</i> measurement
<ul style="list-style-type: none"> Real food matrices <ul style="list-style-type: none"> Carrot Chicken Patatoes Pasta Different food structures (intact, purée, soup) Different salting domestic practices 	Salt localisation Salt diffusion Interactions ²³ Na/food matrix	Saltiness sensory evaluation In mouth Na ⁺ release measurement

ces saltiness without loss



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Health: find **domestic** practices to reduce salt consumption without reducing saltiness

➤ Thanks for your attention



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